VIBRATION TECHNICAL REPORT

AUGUST 2013

Table of Contents

1. Introduction and Project Description 1
1.1 Introduction 1
1.2 Project Description 1
1.2.1 Preferred Alternative 1
2. Regulatory Context and Methodology 3
2.1 Overview of Vibration 3
2.1.1 Vibration from Rail 4
2.1.2 Vibration from Construction 5
2.2 Methodology 5
2.2.1 Analysis Assumptions 7
2.2.2 Vibration Estimation 7
2.3 Criteria 8
2.3.1 FTA Criteria 8
2.3.2 Criteria for Buildings with Extremely Sensitive Equipment 9
2.3.3 Construction Criteria 11
3. Affected Environment 13
3.1 Descriptions of Vibration-Sensitive Land Uses within the Project Corridor 13
3.2 Monitoring of Vibration Sensitive Receptors 14
3.2.1 Monitored Data 14
3.2.2 University of Maryland Campus Vibration Monitoring 20
4. Environmental Consequences 22
4.1 Long-term Operational Effects 22
4.1.1 Potential Mitigation Measures 25
4.1.2 Mitigation 25
4.2 Short-term Construction Effects 26
4.2.1 Avoidance and Minimization 27
4.2.2 Mitigation 27
5. References 28

Appendices

Appendix A – List of Acronyms and Abbreviations
Appendix B – Glossary/Terminology
Appendix C – Instrument Calibration Certificates
Appendix D – Vibration Monitoring Frequency Spectra
Appendix E – MTA Purple Line on UM College Park Campus Term Sheet DRAFT for BOR Discussion April 15, 2011
Appendix F – Purple Line Project, University of Maryland Ambient Vibration Study, August 13, 2009

List of Figures

Figure 1. Typical Vibration Sources 4
Figure 2. Generalized Ground-Borne Vibration Curve 6
Figure 3. Vibration Impact Criteria for Detailed Analysis....10
Figure 4. Vibration Monitoring Locations....16

List of Tables

Table 1. Ground-Borne Vibration Adjustment Factors Utilized for the Purple Line Project 7
Table 2. Ground-Borne Vibration (GVB) and Ground-Borne Noise (GBN) Impact Criteria for General Assessment....8
Table 3. Ground-Borne Vibration (GVB) and Ground-Borne Noise (GBN) Impact Criteria for Special Buildings....9
Table 4. Interpretation of Vibration Impact Criteria for Detailed Analysis....10
Table 5. Vibration Source Levels for Construction Equipment[1]....11
Table 6. Construction Vibration Damage Criteria....12
Table 7. Measured Maximum Vibration Levels Within Study Area 20
Table 8. Predicted Levels of Ground-Borne Vibration....22
Table 9. Predicted Levels of Ground-Borne Vibration with Adjustment Factors Included....24
Table 10. Distance to Potential Construction Damage for Residential Buildings 27

1. Introduction and Project Description

1.1 Introduction

One relatively unique characteristic of light rail transit (LRT) is the associated vibration that comes with operating the system. Since vibration from the implementation of the proposed Purple Line project could potentially impact communities served by the LRT, a general assessment of potential long-term changes in the local vibration environment was determined. In addition, short-term effects related to vibration that would result during the construction phase of proposed improvements and support facilities were also examined. Although the project would be designed to minimize vibration generation, where impacts would be unavoidable, mitigation measures would be implemented where found practical. This *Vibration Technical Report* defines both the anticipated areas where impacts may be unavoidable and possible mitigation measures.

The assessment of vibration for the proposed Purple Line LRT followed procedures outlined in the Federal Transit Administration (FTA) *Transit Noise and Vibration Impact Assessment* (May 2006) manual.

1.2 Project Description

The Purple Line is a proposed 16.2-mile transit line located north and northeast of Washington DC, inside the circumferential I-95/I-495 Capital Beltway. The Purple Line would extend between Bethesda in Montgomery County and New Carrollton in Prince George's County. The "Purple Line corridor" includes five major activity centers: Bethesda, Silver Spring, Takoma/Langley Park, College Park, and New Carrollton.

The purposes of the Purple Line project are the following:

- Provide faster, more direct, and more reliable east-west transit service connecting the major activity centers in the Purple Line corridor at Bethesda, Silver Spring, Takoma/Langley Park, College Park, and New Carrollton,
- Provide better connections to Metrorail services located in the corridor, and
- Improve connectivity to the communities in the corridor located between the Metrorail lines.

The vibration analysis does not assess the effects of the No Build Alternative, or compare the Preferred Alternative to the No Build Alternative. Instead, the Preferred Alternative, as described below, will be compared to FTA vibration impact threshold levels for annoyance and structural damage.

1.2.1 Preferred Alternative

The Preferred Alternative would be at grade except for one short tunnel section and three sections elevated on structures. The Preferred Alternative would operate mainly in dedicated or exclusive lanes, providing fast, reliable transit operations.

There following 21 stations are planned for the Preferred Alternative:

- Bethesda
- Chevy Chase Lake
- Lyttonsville
- Woodside/16th Street
- Silver Spring Transit Center
- Riggs Road
- Adelphi Road/West Campus
- UM Campus Center
- East Campus
- College Park

- Silver Spring Library
- Dale Drive
- Manchester Place
- Long Branch
- Piney Branch Road
- Takoma/Langley Transit Center
- M Square
- Riverdale Park
- Beacon Heights
- Annapolis Road/Glenridge
- New Carrollton

Stations would include ticket vending machines, weather shelters for passengers, lighting, wayfinding and informational signage, trash receptacles, seating, and security equipment such as emergency telephones and closed circuit television cameras. Most riders would walk to the stations or transfer from other transit services. Access plans for each station have been developed to enhance pedestrian and transit access for nearby communities. The stations would have either side or center platforms depending on the site characteristics and space availability.

Two storage and maintenance facilities are proposed: one at Lyttonsville in Montgomery County and the other at Glenridge in Prince George's County. Additionally, traction power substations, used to convert electric power to appropriate voltage and type to power the light rail vehicles, would be required approximately every mile.

As part of the Preferred Alternative the permanent Capital Crescent Trail would be constructed within the Georgetown Branch right-of-way for a distance of 3.3 miles between Bethesda and the CSXT Metropolitan Branch. At the junction with the CSXT the trail is planned to continue on the north side of the CSXT corridor to the SSTC. The permanent Capital Crescent Trail would replace the existing Georgetown Branch Interim Trail which currently extends from Bethesda to Stewart Avenue within the Georgetown Branch right-of-way. The completion of the trail along the CSXT corridor is contingent on agreement with CSXT on the use of their property on the north side of the CSXT tracks for the trail. If agreement is not reached by the time the Purple Line construction occurs, MTA would construct the trail from Bethesda to Talbot Avenue. From Talbot Avenue to Silver Spring an interim signed bike route on local streets would be used. MTA will plan, design, and construct the permanent Capital Crescent Trail between Bethesda and Silver Spring concurrently with the Purple Line. The Capital Crescent Trail will be owned and operated by Montgomery County, which will be responsible for providing the funds to construct it.

2. Regulatory Context and Methodology

2.1 Overview of Vibration

An important consideration for rail transit projects is the vibration that is transmitted from rail movement on the tracks through the ground to adjacent vibration-sensitive buildings. This vibration is caused by the interaction or friction between the wheels and rails resulting in the transmission of vibration waves through the ground. When these ground-borne waves emerge inside the foundation of a building, they may be perceptible to the building occupants. High levels of ground-borne vibration can cause windows, pictures on walls, and/or items on shelves to rattle. However, although the perceived vibration from rail vehicle pass-bys can be intrusive to building occupants, the actual impact from vibration is almost never of sufficient magnitude to cause even minor cosmetic damage to the building structure.

In the natural environment, vibratory motion can best be described as displacement of the particles of an elastic body or medium (the ground) from equilibrium (at rest) by an external agent such as construction equipment striking the ground or train pass-by events at high travel speeds. The displacement of particles creates a back and forth periodic motion or wave that travels through the ground. Soil characteristics such as type, stiffness, and the depth of the water table can dampen or enhance the propagation of ground-borne vibration. In general, ground-borne vibration is more efficient in soils rich in stiff clay and shallow rock.

Ground-borne vibration be described as a velocity, an acceleration, or displacement. However, for the purposes of evaluating the human response to vibration, a velocity descriptor is commonly used. When evaluating human response, ground-borne vibration is usually expressed in terms of a root mean square (RMS) vibration velocity level. RMS is defined as the average of the squared amplitude of the vibration signal. As vibration is a varying quantity, the use of the RMS is the best way to describe its magnitude. To avoid confusion with sound decibels, the abbreviation VdB is used to represent vibration decibels. Because the vibration decibel represents a ratio of the vibration quantity, a reference value should always be specified. For the purposes of this technical report, vibration levels are all referenced to one micro-inch per second (1.0×10^{-6} in/sec).

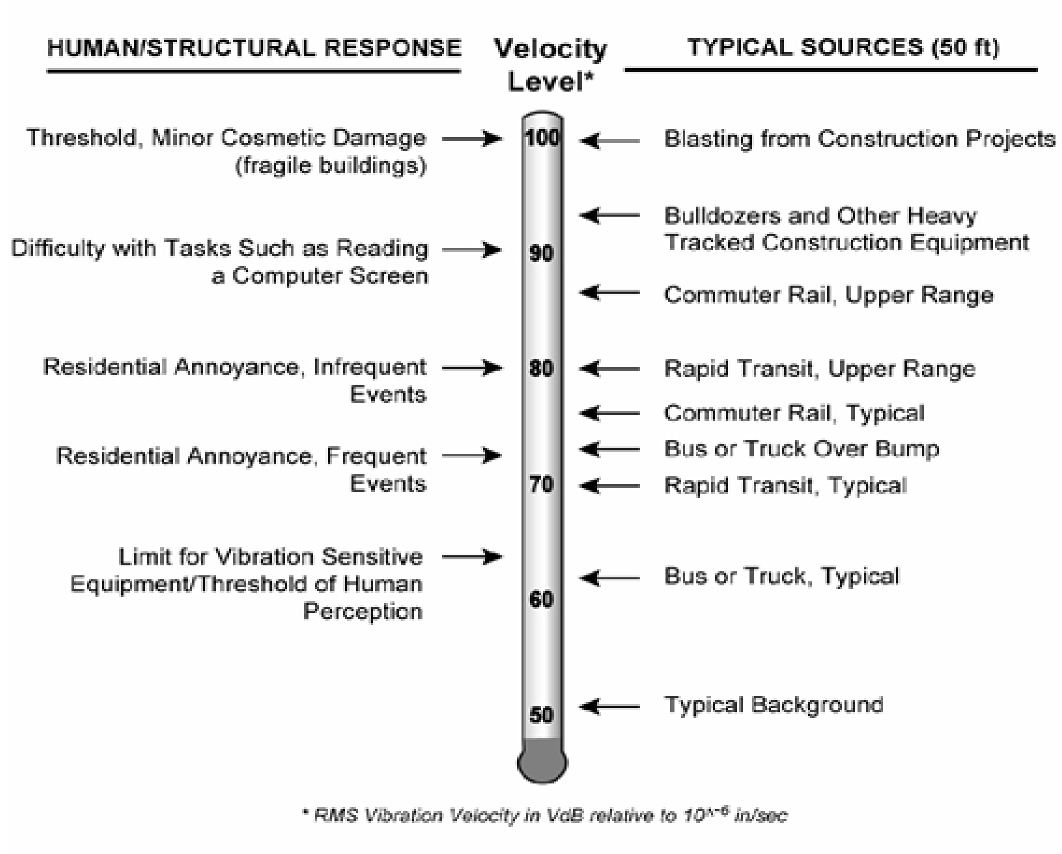
Figure 1 shows typical vibration levels from rail and non-rail sources, as well as the human and structural responses to such levels. Typical vibration levels range from below 50 VdB to 100 VdB (0.000316 in/sec to 0.1 in/sec). The human threshold of perception is around 65 VdB. Unlike airborne noise, most common environmental ground-borne vibration, though present in our surroundings all the time, are generally not perceptible. However, human annoyance from vibration often occurs when vibration levels exceed the threshold of perception by only a small margin. Common sources of perceptible ground-borne vibration include those generated from steel wheeled rail transit movements, construction activities, and some industrial processes. Conversely, vibration generated from traffic movements on roadways are generally below the threshold of perceptibility.

There is substantial experience with vibration from rail systems. In general, this collective experience indicates the following:

- It is rare that ground-borne vibration from transit systems results in building damage, even minor cosmetic damage, as noted above. Therefore, the primary consideration for study purposes is whether vibration will be intrusive to building occupants or will interfere with interior activities or machinery;
- According to the FTA Manual, the threshold for human perception is approximately 65 VdB. Vibration levels in the range of 70 to 75 VdB are often noticeable, but acceptable. Beyond 80 VdB, vibration levels are often considered unacceptable; and,

- Regarding human annoyance, there is a relationship between the number of daily events and the degree of annoyance caused by ground-borne vibration.

Figure 1. Typical Vibration Sources



Source: Federal Transit Administration, Transportation Noise and Vibration Impact Assessment, May 2006.

2.1.1 Vibration from Rail

Vibration from trains is caused by the interaction of the wheels on the rail tracks when moving. The forces caused by this interaction depend on train speed, the smoothness of the rails and wheels, and the resonance frequencies of the vehicle suspension and track support systems. When vibration does occur, it is then radiated into the surrounding ground. The extent to which the vibration waves propagate away from the track depends upon factors such as the strength of the original wave, the depth to bedrock and the soil type. However, the amplitude of the wave is typically diminished with distance. This diminishment in energy results from both the material damping of the wave created by the wave medium and the expansion of the wave front. When the vibration reaches building foundations, it interacts with the building structure and can cause floors, walls and ceilings in living spaces to vibrate. The Purple Line project would introduce LRT (light steel-wheel urban transit trains) into areas that currently do not have this source of vibration. Typical LRT trains produce similar vibration levels as heavy steel-wheel urban transit trains since they both have similar axle suspension systems.

Sometimes vibration is also manifested as ground-borne noise. Ground-borne noise is the radiation of acoustical energy from ground and structural surfaces excited by ground-borne vibration. The noise produced is the result of the acoustic energy propagating through rock, soil or a receiving structure medium into the air of an underground room such as a basement or other below grade structures. However, ground-borne rail noise is generally only an issue for trains that operate under ground. For systems where the train is operating either at or above grade, the airborne noise level is generally significantly louder than the ground-borne noise. As a result, the ground-borne noise is typically masked by the airborne noise. Where short-length tunnels are proposed along the Purple Line project corridor, the potential for ground-borne noise effects were considered.

2.1.2 Vibration from Construction

An additional source of vibration would be related to the construction of the proposed Purple Line. The operation of construction equipment causes ground vibrations which spread through the surrounding ground. While these vibrations tend to diminish over distance, depending upon the type of construction equipment, duration of the activity, nearby sensitive receptors could be affected. Human annoyance from construction is typically dependent upon the extent, distance and duration of the vibration generating activities. As with vibration created from train operations, construction-related vibration rarely causes structural damage to normal building structures. However, some building damage can occur when construction-related activities are near older, more fragile historic buildings. As a result, construction-related vibration impact criteria give special consideration to these fragile buildings. Construction activities that typically generate the most severe vibration include blasting and impact pile driving. For the Purple Line project, blasting would occur at the Plymouth Street Tunnel area, and pile driving would be utilized at various locations along the project corridor where bridges, retaining walls and other structural challenges would require them.

2.2 Methodology

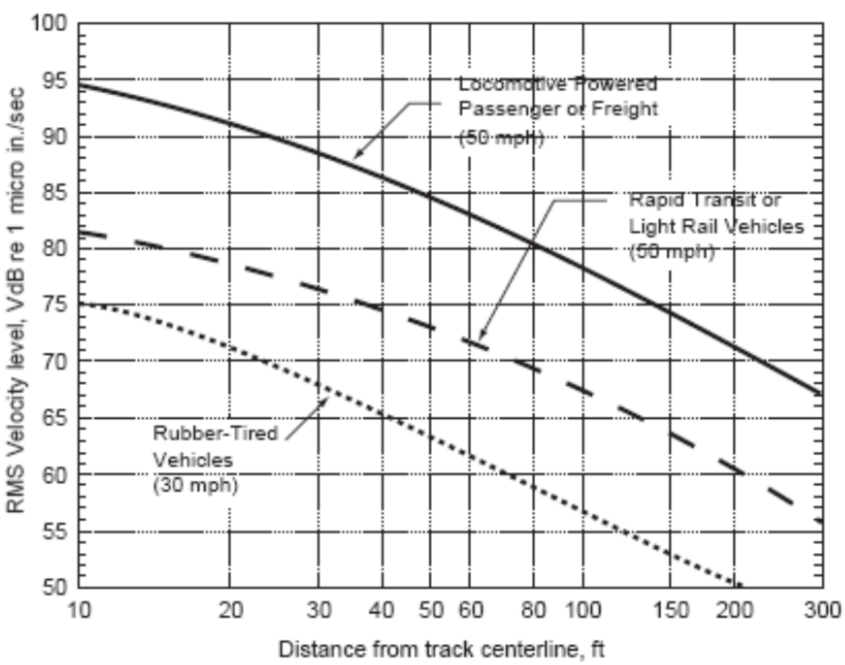
The procedures utilized for this technical report were based on general assessment guidelines contained in FTA's *Transit Noise and Vibration Impact Assessment* (May 2006). This vibration assessment approach, recommended by FTA for projects such as the Purple Line, was utilized to determine the potential for impacts:

- **Identification of Vibration-sensitive Receptors:** Vibration-sensitive land uses along the project corridor were identified using aerial photography and available GIS mapping, and were subsequently field verified. Additional existing site conditions, including other potential vibration-sensitive receptors were noted during field visits. As defined in the FTA Manual, section 8.1.1, vibration sensitive receptors are defined as those building structures where the effect of exterior vibration levels may result in annoyance to occupants. These may include residential and or institutional land uses. However, most of the sensitive receptors analyzed in this report were residential in character. Receptors were then grouped together based on their location relative to the proposed transitway and other geographic factors that might influence project-related vibration levels. Within each grouping, a representative receptor location was determined for modeling purposes. Extremely vibration sensitive locations were also identified (FTA Manual, Section 8.1.1). These locations include university research laboratories where even low levels of vibration may cause unacceptable interference with interior operations.
- **Determination of Existing Baseline Vibration Levels:** Monitoring of existing vibration levels was conducted at representative receptor locations along the project corridor. To obtain a representative

measurement, monitoring was conducted for several minutes, depending upon the volume of traffic in the area and anticipated vibration events such as pass-bys of trains and buses. Monitoring for all sites was conducted outdoors except at the receptor location within the basement of Dorchester Hall on the UMD Campus (as requested by the University). A total of 23 representative locations were monitored for vibration.

- **Vibration Distance Screening:** If representative receptors were located further away than the specified vibration screening distances identified within the FTA Manual, impacts related to rail vibration were deemed unlikely to occur. The screening area for the vibration analysis depends upon the FTA defined land use categories. For residential land uses, the screening distance is a 150-foot assessment zone defined from the alignment. This distance is reduced to 100 feet for institutional uses, and expanded to 450 feet for special buildings, such as concert halls and recording studios, which may be particularly sensitive to vibration. Accordingly, only receptors that could be potentially affected by the proposed Purple Line Project were considered in the assessment.
- **Estimation of Future Vibration Levels:** For the remaining residential and institutional receptors (those not eliminated by the screening process), FTA general assessment procedures were used to estimate future vibration levels resulting from the proposed project conditions. Generalized ground-borne vibration curves provided in the FTA Guidance Manual (Refer to Figure 2) were utilized, along with the relevant speed adjustment equations. For those properties at which impacts are estimated, further adjustments were made to the generalized curve values for foundation coupling loss, floor to floor attenuation and building resonance gain. For extremely sensitive research equipment operating within the UMD Campus, the currently agreed upon criteria was utilized to assess the potential for immediate impact from the proposed project.
- **Mitigation Recommendations:** Potential measures to reduce or mitigate future potential vibration impacts were recommended as necessary.

Figure 2. Generalized Ground-Borne Vibration Curve



Source: Federal Transit Administration, Transit Noise and Vibration Impact Assessment, May 2006.

2.2.1 Analysis Assumptions

In order to conduct the vibration general assessment, assumptions related to operational data and methodological approach were included in the analysis based on the following references:

- Preliminary RailSIM® TPC Theoretical Running Time Results (April 2012) were used to determine speed assumptions.
- Purple Line Project Design Criteria define peak period headways of six minutes and off-peak period headways of between 10 and 12 minutes.
- A total of 30 freight trains operate daily along the CSX line.

2.2.2 Vibration Estimation

The FTA generalized ground surface vibration curves, shown on Figure 2 above, were utilized to estimate vibration impacts along the project corridor. The generalized vibration curves are based on the type of rail vehicle and the receptor to track distance. The curve is based on a reference speed of 50 mph.

Vibration levels estimated using the generalized curves were subsequently adjusted based on the projected Purple Line train speed using the following equation:

$$\text{Speed Adjustment (dB)} = 20\text{Log}\left(\text{Speed}_{actual} / \text{Speed}_{ref}\right)$$

Where,

Speed_{actual} = Actual speed of train

Speed_{ref} = Reference speed of 50 mph used for LRT trains

The majority of vibration sensitive receptors evaluated consist of residential buildings. In those cases where vibration impacts are found to occur using the above procedure, a further refinement of the vibration analysis is provided utilizing additional FTA adjustment factors specifically related to the properties of the impacted building (i.e. foundation coupling loss, floor to floor attenuation and building resonance gain). As shown below in Table 1, these adjustment values differ between typical single-family wood framed homes and larger masonry buildings.

Table 1. Ground-Borne Vibration Adjustment Factors Utilized for the Purple Line Project

Adjustment Factor	Adjustment Parameters	Adjustment
Coupling to Building Foundation	Wood Frame Houses	-5 dB
	1-2 Story Masonry	-7 dB
	3-4 Story Masonry	-10 dB
	Large Masonry on Piles	-10 dB
Floor to Floor Attenuation [1]	1st Floor	-2 dB
Wall, Floor and Ceiling Amplification [2]	-	6 dB

[1] Since upper floors provide additional attenuation, the first floor attenuation was conservatively assumed for use in the assessment as a worst case.
[2] Represents a conservative value, assumed for all building types.

Source: Federal Transit Administration, Transit Noise and Vibration Impact Assessment, May 2006.

2.3 Criteria

2.3.1 FTA Criteria

The FTA ground-borne vibration impact criteria utilized for the proposed project are based on the maximum single event ground vibration caused by a rail vehicle pass-by. Two additional factors that help define the FTA vibration criteria include the use of three distinct building categories and the use of a higher and a lower impact threshold that is dependent upon the number of project-related rail events per day. For the proposed Purple Line project, more than 70 vibration events would occur during a typical day. This would fall into FTA's "frequent events" category as shown in Table 2 and apply only to the indoor spaces of buildings because human annoyance resulting from ground-borne vibration requires the interaction of the ground vibration within a building structure. Table 2 shows that the ground-borne vibration (GBV) criteria threshold for the institutional uses is not as demanding since the sensitivity to vibration for the residential use is greater.

Table 2 also includes separate FTA criteria for ground-borne noise (GBN), or the "rumble" that can be radiated from the motion of room surfaces in buildings due to ground-borne vibration. Although expressed in dBA, which emphasizes the more audible middle and high frequencies, the criteria are set significantly lower than for airborne noise to account for the annoying low-frequency character of ground-borne noise. As airborne noise often masks ground-borne noise for above ground (i.e. at-grade or elevated) transit systems, ground-borne noise criteria, as described in the FTA manual, are primarily applied to below grade operating rail conditions such as the Plymouth Street Tunnel. The threshold of human perceptibility for ground-borne noise is 25 to 40 dBA for low and medium frequency noise, respectively.

Table 2. Ground-Borne Vibration (GVB) and Ground-Borne Noise (GBN) Impact Criteria for General Assessment

Land Use Category	GBV Impact Levels (VdB re: 1 micro-inch / sec)			GBN Impact Levels (dB re: 20 micro Pascals/ sec)		
	Frequent Events [1]	Occasional Events [2]	Infrequent Events [3]	Frequent Events [1]	Occasional Events [2]	Infrequent Events [3]
Category 1: Buildings where vibration would interfere with interior operations	65 VdB	65 VdB	65 VdB	NA [4]	NA [4]	NA [4]
Category 2: Residences and buildings where people normally sleep	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primary daytime use	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

[1] "Frequent Events" is defined as more than 70 vibration events per day.
[2] "Occasional Events" is defined as between 30 and 70 vibration events per day.
[3] "Infrequent Events" is defined as less than 30 vibration events per day.
[4] N/A means "not applicable". Vibration-sensitive equipment is not sensitive to ground-borne noise.

Source: Federal Transit Administration, Transit Noise and Vibration Impact Assessment, May 2006.

The FTA vibration impact criteria provided in Table 2, does not specifically account for existing sources of vibration. However, the existing environment may currently cause a significant number of perceptible GBV or GBN events, regardless of the vibration components of a proposed project. Because of this, FTA established several separate criteria and methods of analysis depending upon the existing rail environment defined as follows:

- Infrequently-used rail corridor (corridors with fewer than five trains per day). Use the general vibration impact criteria (Table 2).
- Moderately-used rail corridor (corridors with five to twelve trains per day). If existing vibration exceeds the general vibration impact criteria and if estimated vibration levels are at least five VdB less than existing vibration, there would be no impact from the proposed project. For other situations, use the general vibration impact criteria.
- Heavily-used rail corridor (corridors with more than twelve trains per day). If existing vibration exceeds the general vibration impact criteria and if the proposed project would double the number of vibration events, the project would cause additional impact. If estimated vibration levels for the proposed project would be three VdB or less than existing vibration, there would be no impact.

In addition to the potentially impacted land uses described in Table 2, the FTA has developed vibration impact criteria for "special buildings", which may include uses such as concert halls, theatres and recording studios where there is greater sensitivity to vibration. Because of the unique and varied sensitivity of these uses, separate criteria are utilized to address potential vibration-related impacts. Table 3 gives criteria for acceptable levels of ground-borne vibration and noise for various types of "special buildings."

Table 3. Ground-Borne Vibration (GVB) and Ground-Borne Noise (GBN) Impact Criteria for Special Buildings

Land Use Category	GBV Impact Levels (VdB re: 1 micro-inch / sec)		GBN Impact Levels (dB re: 20 micro Pascals/ sec)	
	Frequent Events [1]	Occasional or Infrequent Events [2]	Frequent Events [1]	Occasional or Infrequent Events [2]
Concert Halls	65 VdB	65 VdB	25 dBA	25 dBA
TV Studios	65 VdB	65 VdB	25 dBA	25 dBA
Recording Studios	65 VdB	65 VdB	25 dBA	25 dBA
Auditoriums	72 VdB	80 VdB	30 dBA	38 dBA
Theatres	72 VdB	80 VdB	35 dBA	43 dBA

[1] "Frequent Events" is defined as more than 70 vibration events per day.
[2] "Occasional or Infrequent Events" is defined as fewer than 70 vibration events per day.

Source: *Federal Transit Administration, Transit Noise and Vibration Impact Assessment, May 2006.*

2.3.2 Criteria for Buildings with Extremely Sensitive Equipment

Several buildings within the University of Maryland (UMD) Campus either contain equipment that is sensitive to vibration or utilize processes that are extremely vibration-sensitive. MTA and UMD have agreed to the use of specific vibration impact criteria for buildings where extremely sensitive equipment or instruments operate (see Appendix E). As shown in Table 4 and Figure 3, these additional criteria are derived from frequency based vibration curves (VC) defined by the International Organization for Standardization (ISO) and a report from the Institute of Environmental Sciences and Technology (IEST) "IES-RP-CC-12.1, "Considerations in Clean Room Design."

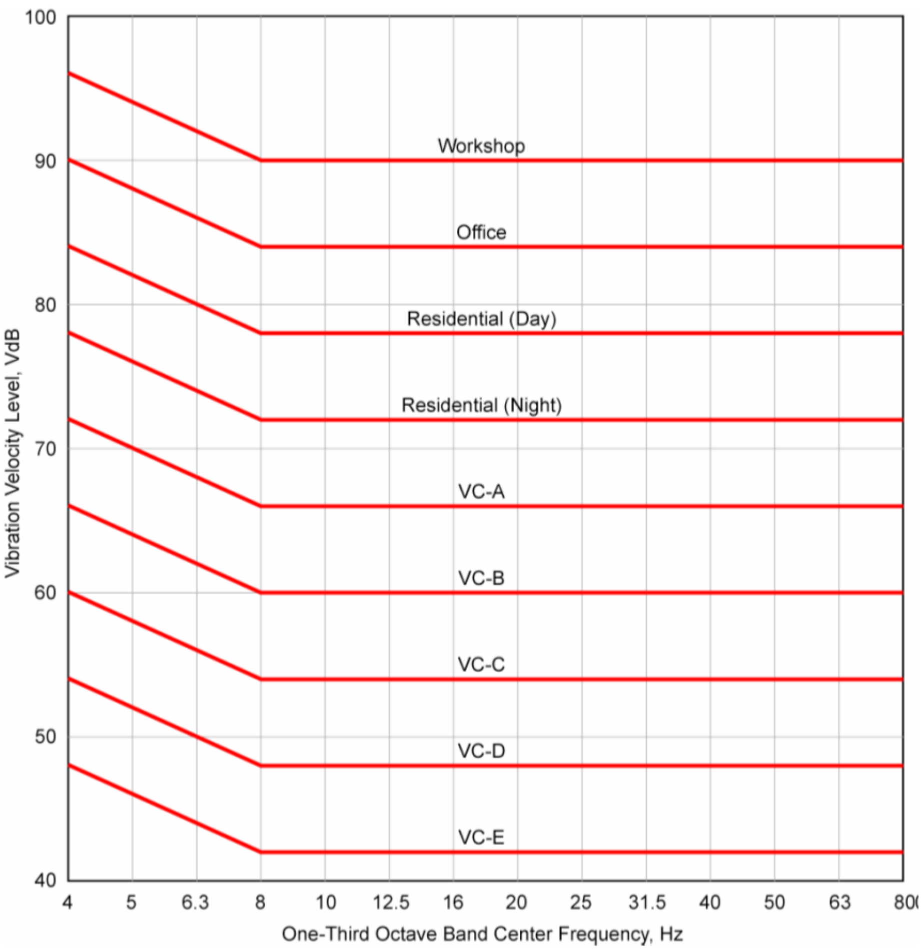
Table 4. Interpretation of Vibration Impact Criteria for Detailed Analysis

VC Curve Name	Vibration Limit		Intended Use
	Micro-inch/second	VdB[1] re 1 u-ips	
VC-A	2,000	66	Adequate for medium- to high-power optical microscopes (400X), microbalances, optical balances, and similar specialized equipment.
VC-B	1,000	60	Adequate for high-power optical microscopes (1000X), inspection and lithography equipment to 3 micron line widths.
VC-C	500	54	Appropriate for most lithography and inspection equipment to 1 micron detail size.
VC-D	250	48	Suitable in most instances for the most demanding equipment, including electron microscopes operating to the limits of their capability.
VC-E	125	42	The most demanding criterion for extremely sensitive equipment.
VC-F[1]	63	36	Not described.
VC-G[1]	31	30	Not described.

[1] For VC-F and VC-G, the IEST criteria is beyond that which is recommended by FTA.

Source: Federal Transit Administration, Transit Noise and Vibration Impact Assessment, May 2006.

Figure 3. Vibration Impact Criteria for Detailed Analysis



Source: Federal Transit Administration, Transit Noise and Vibration Impact Assessment, May 2006.

The criteria are wave frequency dependent since highly sensitive experiments or operations may be more responsive within particular frequency range of octave bands. More recently, the National Institute of Standards and Technology (NIST) developed a NIST–A criteria curve for nano-technology. The NIST-A curve is identical to the VC-E curve at frequencies above 20 Hz, but is more stringent than the VC-E curve at frequencies below 20 Hz.

While these criteria are the result of sound research, further examination of project-related vibration may indicate that criteria levels related to 1) manufacturers requirements or 2) the existing vibration environment may be more appropriate. The current understanding between the MTA and the UMD states that where the proposed transitway would be adjacent to vibration sensitive facilities, the project should be designed to minimize ground-borne vibration consistent with proven industry practices, and maintenance requirements should be designed to meet the greater of the ambient vibration levels or the National Institute of Standards and Testing (NIST) level A (or 42 VdB above 20 Hz) within 100 feet of the nearest track centerline at existing and potential research laboratories for a period of 30 years (refer to the term sheet in Appendix E).

2.3.3 Construction Criteria

Although ground-borne vibration related to human annoyance (generally expressed in units of "VdB") is the primary concern during project operation, potential building damage is the concern during the construction phase.

Building damage can occur from construction-related vibration as a result of displacement (movement) of a building over time and therefore the structural damage criteria is expressed in particle velocity rather than the vibration decibel level. Consequently, construction vibration is expressed as Peak Particle Velocity (PPV) in units of inches per second. Source vibration levels for some typical construction equipment are shown below in Table 5. The FTA's construction vibration damage criteria are also shown below in Table 6. The FTA's construction vibration damage criteria indicate that for non-engineered timber and masonry buildings, typical of structures located near the proposed transitway, the PPV should not exceed 0.2 inches per second.

Table 5. Vibration Source Levels for Construction Equipment[1]

Equipment		PPV at 25 ft (in/sec)	Approximate L_V[2] at 25 ft
Pile Driver (Impact)	Upper Range	1.518	112
	Typical	0.644	104
Pile Driver (Vibratory)	Upper Range	0.734	105
	Typical	0.17	93
Vibratory Roller		0.21	94
Hoe Ram		0.089	87
Large Bulldozer		0.089	87
Caisson Drilling		0.089	87
Loaded Trucks		0.076	86
Jackhammer		0.035	79
Small Bulldozer		0.003	58

[1] FTA damage criterion is 102 Vdb for fragile buildings and, 90 VdB for extremely fragile historic buildings
[2] RMS Velocity in decibels (VdB) re: 1 micro-inch/second

Source: Transit Noise and Vibration Impact Assessment, FTA, 2006

Table 6. Construction Vibration Damage Criteria

Building Category	PPV (in/sec)	Approximate L_v[1]
I. Reinforced-concrete, steel or timber (no plaster)	0.5	102
II. Engineered concrete and masonry (no plaster)	0.3	98
III. Non-engineered timber and masonry buildings	0.2	94
IV. Buildings extremely susceptible to vibration damage	0.12	90

[1] RMS velocity in decibels (VdB) re 1 micro-inch/second

Source: Transit Noise and Vibration Impact Assessment, FTA, 2006

3. Affected Environment

Vibration-sensitive land use was identified by screening GIS data maps for buildings with primarily residential or institutional uses nearby the project corridor. Observations from field reconnaissance was utilized to verify GIS data map observations and to identify any additional sensitive land use locations within the larger study area.

3.1 Descriptions of Vibration-Sensitive Land Uses within the Project Corridor

Following are summary descriptions of vibration-sensitive land uses within the project corridor:

- Near the western project terminus along Elm Street, Oakridge Lane, and Lynn Drive are 37 single-family residences which would be located approximately 100 feet on the south side of the transitway between 47th Street and East West Highway. As the project corridor approaches the East West Highway, there are also apartment buildings along Montgomery Avenue, and an apartment building at the corner of Montgomery Avenue and East West Highway within the corridor.
- Several single-family residences are located on both sides of the proposed transitway between East West Highway and the Columbia Country Club Golf Course. These houses are located approximately 50 feet from the rail centerline.
- East of the Columbia Country Club Golf Course extending to Connecticut Avenue, several multi-family residences are located approximately 130 feet north of the rail centerline.
- Additional single- and multi-family residences are located between Connecticut Avenue and Jones Mill Road. Residences are located approximately 60 to 200 feet from the proposed transitway centerline.
- Between Jones Mill Road and the point where the project corridor starts to run parallel to the existing CSX freight rail line, several multi-family residences exist along Freeman and Terrace Drives approximately 80 feet south of the rail corridor. Five single-family homes also exist along Talbot Avenue, approximately 80 feet south of the project centerline. Rosemary Hills Elementary School is located approximately 60 feet from the transitway centerline on Talbot Avenue.
- As the proposed transitway continues to run parallel to the existing CSX freight rail line, the existing MTA rail line rises from below grade to run parallel to the freight line. In this area, several single- and multi-family homes exist approximately 30 to 50 feet south of the proposed rail centerline.
- As the project corridor begins to rise to a super-elevated position and is about to cross over the existing CSX and MTA rail lines, several multi-family dwellings exist within 20 feet south of the proposed transitway.
- Sixty-five single-family residences exist along Wayne Avenue from Fenton Street to the Sligo Creek Trail approximately 60 to 80 feet from the rail centerline. One recording studio was also identified along Wayne Avenue near Cedar Street. Silver Spring International Middle School is located approximately 60 feet from the transitway centerline, on Wayne Street near Mansfield Road.
- Several multi-family residences exist from where the proposed transitway crosses Sligo Creek Trail to where it starts to traverse the Plymouth Street tunnel. Fourteen single-family residences exist along Plymouth Street to Arliss Street approximately 50 feet from the rail corridor.
- Seventeen single-family residences are located approximately 70 feet north of the project corridor along Arliss Street. From Arliss Street to University Boulevard East, there are numerous multi-family buildings approximately 60 to 70 feet from the project corridor.
- Along University Boulevard East, between Piney Branch Road and where the project corridor enters the UMD Campus, numerous single- and multi-family dwellings exist along the project corridor. These vibration sensitive properties are interspersed with commercial development, which is

considered non-sensitive. Distances from the vibration-sensitive properties to the project centerline vary between approximately 60 and 120 feet.

- Within the UMD Campus, one student residence hall exists along Campus Drive, located approximately 90 feet south of the transitway centerline. Along Yale Avenue, student residence buildings exist approximately 75 feet south of the project centerline. In addition, several buildings within the campus site which contain extremely vibration-sensitive electronic equipment are located along the Campus Drive within the project corridor. The closest of these buildings is approximately 65 feet from the proposed transitway centerline.
- Four single-family residences exist along Paint Branch Parkway between Rhode Island Avenue and Dartmouth Avenue approximately 85 feet south of the project centerline.
- Three single-family residences exist along Kenilworth Avenue approximately 80 feet east of the project centerline. Also, 32 single-family residences exist along Kenilworth Avenue, with each building sitting approximately 140 feet west of the project centerline.
- Twenty single-family residences are located along Riverdale Road. The homes are approximately 80 feet from the project centerline.
- Multi-family units are present along Riverdale Road and 67th Avenue, and are approximately 50 feet from the transitway centerline.
- Three single-family residences exist near the intersection of Riverdale Road and Veterans Parkway, approximately 120 feet from the project centerline.
- Several multi-family residences are present near the intersection of Ellin Road and Veterans Parkway, approximately 120 feet from the project corridor.
- Near the eastern project terminus, 14 single-family residences are located along Ellin Road near Hanson Oaks Drive, approximately 60 to 120 feet from the project corridor.

3.2 Monitoring of Vibration Sensitive Receptors

Existing vibration measurements were taken at several key locations along the project corridor, with locations being selected based on their close proximity to the project corridor and their ability to represent clusters of other similarly affected residences. Monitoring of existing vibration levels is often useful in the determination of vibration impacts, particularly when extremely sensitive receptors (such as research laboratories or recording studios with vibration-sensitive equipment) are located within the study area. However, because existing residential environments do not normally involve major ground-borne vibration events, existing vibration levels are generally not required by the FTA as input for vibration prediction procedures. When existing vibration levels are recorded during the early stages of a project, they are typically only used to document that the existing vibration environment is as expected, less than the range of human perception. Moreover, because some residences along the project corridor are located near existing rail lines, measurements are helpful to document whether the existing vibration levels at these properties would be greater than the project vibration.

3.2.1 Monitored Data

Monitoring was conducted between December 5th and December 8th, 2011. Vibration measurements were collected with a Crystal Instruments Handheld Dynamic Signal Analyzer and Vibration Data Collector, Model Number CoCo-P04. A PCB Piezotronics High Sensitivity ICP Accelerometer (10V/g), Model Number 393B31 was used in conjunction with the vibration analyzer. A calibration certificate for the accelerometer is included in Appendix C.

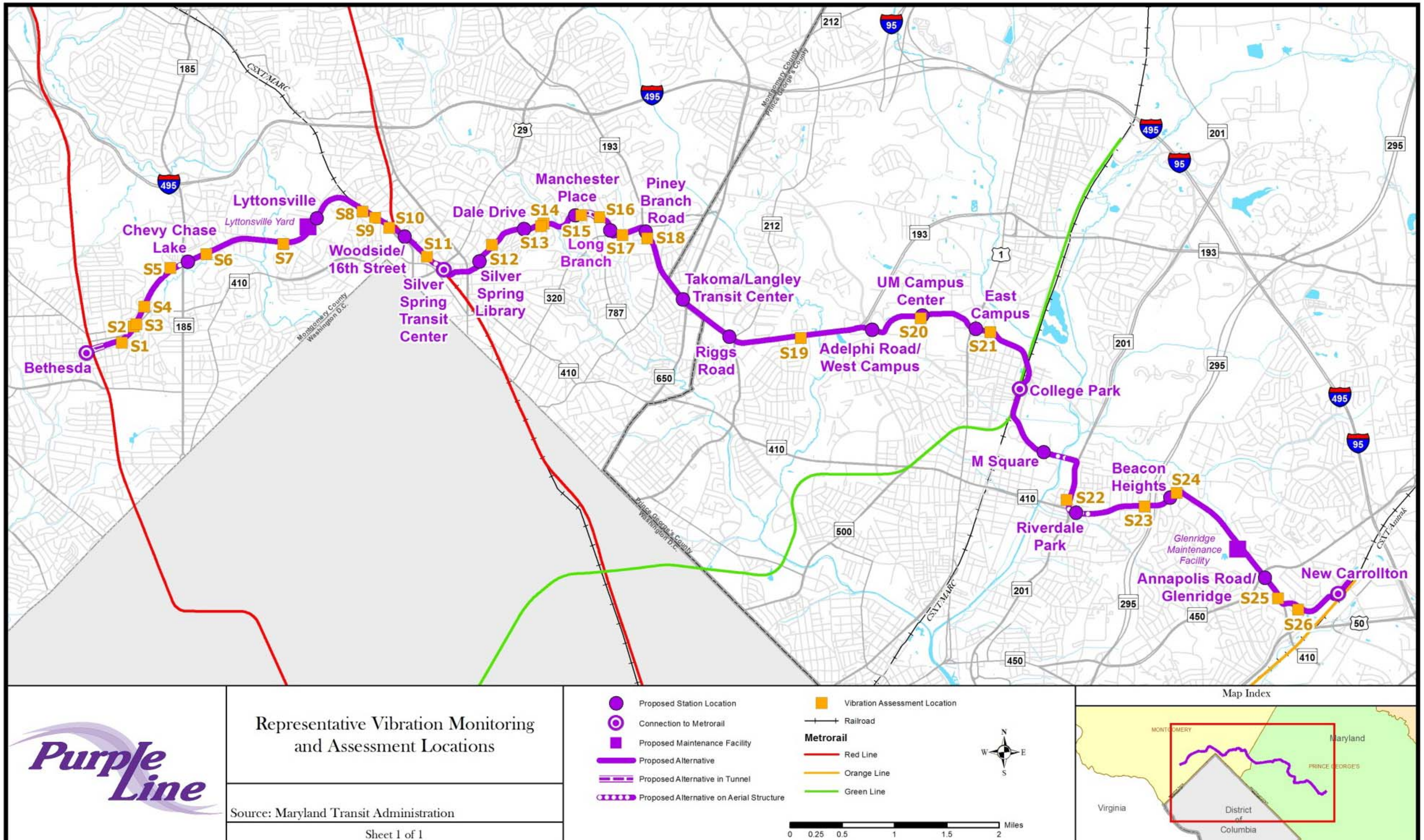
The monitoring sites were selected on the basis of several factors, the most important of which was the site's potential sensitivity to changes in vibration levels. Selected monitoring locations were either representative of a unique vibration environment or that of similarly situated receptors nearby. Since the project corridor passes near many residential districts, the majority of the selected sensitive receptors were residential properties. Outdoor recreational areas, commercial or industrial land uses were not chosen as monitoring sites because these types of land uses are not included in the FTA vibration land-use category list of vibration sensitive uses.

Vibration measurements were collected to attempt to capture the maximum ambient vibration levels within the Purple Line project study area. Vibration monitoring was typically conducted for approximately five minutes duration or until a sufficient number of representative traffic or rail movements were observed. For example, if a vibration sensitive receiver would be affected by traffic along a bus route, a single bus pass-by event had to occur before the monitoring session was considered complete. At other locations where existing rail activity occurred, readings typically accounted for multiple rail pass-by movements. There were, however, many locations where vibration levels were not affected by traffic, as there was little to no vehicular activity nearby. The majority of the readings were recorded on a concrete slab closest to the affected property to obtain the maximum existing vibration level affecting a given receptor site and to ensure only ambient ground-borne vibration levels could be measured without interference from the resonant movements of the receptor site itself.

Monitoring locations are described below and are depicted in Figure 4. Baseline vibration monitoring was not completed at sites S8, S10, and S13, but these locations were assessed for vibration impact exposure from Purple Line operations. A description of each of the vibration assessment locations is provided below:

- Site S1 is located along the south side of the project corridor at a single-family residence at 4309 Elm Street. This home is representative of numerous single-family homes along Elm Street. Existing vibration levels measured at site VS1 came primarily from the very limited automobile traffic that currently exists along Elm Street. The monitor was located in front of the building along Elm Street.
- Site S2 represents a large multi-story apartment complex at 4242 Montgomery Avenue. The building sits at the intersection of East West Highway and Montgomery Avenue, both of which are heavily traveled by buses and trucks. These traffic movements appear to contribute to ground-borne vibration in the area. Building generators or other machinery also contribute to vibration. The monitor was located at the rear of the building facing the project corridor, which was a considerable distance from the roadway. As such, the main vibration source appears to be from a building generator.
- Site S3 is a single-family residence located at 4230 East West Highway. It is near the southeast corner of the intersection of the existing Georgetown Branch Trail and East West Highway. This home is also representative of the residences on Lynn Drive. The large number of heavy trucks and buses that travel along East West Highway are the main contributors of vibration to this site. This site is also more representative of the influence of the noise on S2 above as it is closer to the roadway. The monitor was located in front of the house along the trail side closest to the trail.
- Site S4 is a single-family home located at 4104 Edgevale Court. The rear of the home faces the east side of the project corridor. This home is representative of other nearby residential properties on Kentbury Drive and Edgevale Street that are primarily affected by vibration from automobile movements on local access roadways. The monitor was located on the driveway in the front of the building.

Figure 4. Vibration Monitoring Locations



- Site S5 is a multi-family apartment complex which is located along the project corridor at 3929 Newdale Road. In this area, Newdale Road is essentially a dead end street adjacent to the Columbia Country Club Golf Course, and as a result, there are no direct traffic-related vibration effects. This residence is representative of the other multi-family apartments along Newdale Road. The monitor was located near the parking lot.
- Site S6 at 3607 Chevy Chase Lane represents a series of residential townhouse buildings that are adjacent to the west and east side of the project corridor along Chevy Chase Lane and Manor Road, respectively. Additionally, some single-family residences exist along West Coquelin Terrace and Jones Bridge Court. With the exception of vehicle movements within the nearby parking lots and on a few local streets, residential buildings closest to the project corridor are not affected by any significant vibration events. The monitor was located at the rear of the building along the Georgetown Branch Trail.
- Site S7 is an apartment complex located at 2825 Terrace Drive to the south of the project corridor. Traffic-related vibration is not a major factor; however, there is an industrial facility on the north side of the project corridor where the movements of heavy trucks appear to affect vibration levels near the apartment buildings. The monitor was located at the far end of the building complex closest to the Georgetown Branch Trail.
- Site S9 is located at the Barrington Apartments at 1946 Rosemary Hills Drive, which is just south of the project corridor. At this point, the project corridor is directly adjacent to the CSXT freight rail line. Two freight train movements were recorded during the vibration monitoring session. The effect of these “at-grade” train movements near the buildings was clearly noticeable. In addition to the apartment buildings, these measurements represent several single-family residences along Talbot Avenue and Leonard Court. The Rosemary Hills Elementary School also exists along Talbot Avenue. The monitor was located at the side of the building closest to the existing freight traffic.
- Site S11 is located at 1515 East Falkland Lane and represents the Falkland Apartment Complex with several buildings. The buildings are located to the south of the project corridor and are affected by both CSXT freight and MTA commuter trains. The existing tracks at this location are in a cut section that is approximately 20 to 30 feet below grade. The monitor was located at the side of the building closest to the existing freight traffic.
- Site S12 is a commercial building located at 801 Wayne Avenue. Wayne Avenue is a major traffic corridor. The monitoring site is representative of numerous single-family residences along Wayne Avenue. Traffic along Wayne Avenue includes buses and some trucks. These traffic conditions define the vibration levels in this area. The monitor was located in front of the building facing Wayne Avenue.
- Site S14 is located at 301 Mansfield Road at the intersection of Wayne Avenue. Very little traffic exists along Mansfield Road, but traffic along Wayne Avenue includes numerous buses and some trucks. These traffic conditions define the vibration levels in this area. This location is representative of other single- and multi-family homes along Wayne Avenue. The Silver Spring International School is also located along this segment of Wayne Avenue. The monitor was located in front of the building at the corner of Wayne Avenue and Mansfield Road.
- Site S15 is located at 8804 Plymouth Street. This location is representative of several town homes and single-family homes that are in the vicinity of Plymouth Street and Flower Avenue as the project corridor would traverse a proposed tunnel section at this location. Limited traffic volume along Plymouth Street results in vibration levels that are marginally traffic-related. Flower Avenue however, does experience more significant vehicular traffic. The monitor was located in front of the building.

- Site S16 is located at 8831 Arliss Street near the project corridor where the tracks would be transitioning between a tunnel and an at-grade elevation. A row of representative homes along Arliss Street would be located just north of the project corridor. As Arliss Street gradually turns southward, additional multi-family buildings are located east of the project corridor. Existing vibration levels would be related to traffic along Arliss Street which would primarily consist of automobiles. The monitor was located in front of the building.
- Site S17 is an apartment building complex located at 8629 Piney Branch Road. The location is representative of several apartment complex buildings on both the north and south sides of the project corridor. Vehicular traffic is the dominant vibration source in the area as Piney Branch Road is a major access road for trucks and buses. The monitor was located in front of the building.
- Site S18 is a single-family home located at 727 University Boulevard. The location is a major commercial route, and there are several single- and multi-family dwellings on either side of the project corridor for which this property is representative. Vehicular traffic is the dominant vibration source in the area as University Boulevard is a major access route for trucks and buses. The monitor was located along the driveway in front of the building.
- Site S19 is a single-family home located at 2421 University Boulevard East. The location is a major commercial route, and there are several single-family dwellings on the south side of the project corridor for which this property is representative. Vehicular traffic is the dominant vibration source in the area as University Boulevard East is a major access route for trucks and buses. The monitor was located in front of the building.
- Site S20 is located on the UMD Campus at Dorchester Hall. It is the only residential building that would be close to the project corridor as it travels along Campus Drive. As this section of Campus Drive is a major hub for buses, the vibration levels are reflective of the bus traffic. Readings were taken both inside and outside of the building at locations closest to Campus Drive. Inside readings were taken in the basement. The monitor for both inside and outside locations was located in front of the building facing Campus Drive.
- Site S21 is located on the UMD Campus at Leonard Town Hall. The project corridor, as it travels along Rossborough Lane, is approximately 50 feet from the closest residential building, Number 244. In this area of the campus, university shuttle buses do stop in the nearby parking lot. The monitor was located in front of the building facing the parking lot.
- Site S22, located at 3419 Quintana Street on the western side of the project corridor, is a single-family home that is representative of a series of single-family homes along Kenilworth Avenue. Homes closest to Kenilworth Avenue would be taken by the project. VS19 represents the second row of homes from Kenilworth Avenue, which as a result of the project would become the closest properties to the proposed transitway. Traffic on Quintana Street and along Kenilworth Avenue is the main source of vibration in the area. The monitor was located in front of the house facing Quintana Street.
- Site S23, located at 6002 Eastpine Drive on the southern side of the project corridor, is a single-family home that is representative of a series of single-family homes along Riverdale Road. Homes closest to Riverdale Road would be taken by the project. VS20 represents the second row of homes from Riverdale Road, which as a result of the project would become the closest properties to the proposed transitway. Traffic on Eastpine Drive and on Riverdale Road is the main source of vibration in the area. The monitor was located at the side of the building facing Riverside Road.
- Site S24 represents a series of buildings at 6751 Riverdale Road that make up the East Pines Apartments. Existing traffic conditions along Riverdale Road are the primary source of vibration. The monitor was located along 67th Place at the side of apartment complex.

- Site S25 represents a series of apartment complexes along the western side of Veterans Parkway just before the project corridor turns east onto Ellin Road. Heavy traffic traveling at high speeds currently exists along Veteran Parkway. The monitor was located in the parking lot closest to Veterans Parkway.
- Site S26 is located just south of the project corridor near Ellin Road. The monitoring location is representative of several townhouses that exist nearby the project corridor. Existing vibration levels result from the limited traffic that accesses the townhouse parking areas. The monitor was located at the side of the building closest to Ellin Road.

Table 7 summarizes the monitored data, noting the maximum recorded vibration level at each site. Representative vibration spectra are provided in Appendix D within the frequency ranging from 5 to 250 Hz. Maximum vibration levels tended to occur in the 15 to 50 Hz range, which is very typical of the vibration characteristics found in residential areas.

As the threshold of human perception for vibration is approximately 65 VdB, following is a description of the monitoring sites at which the existing vibration levels would be above this level of perception.

- Site S9 is located at an apartment complex that is very close to the existing CSXT freight line. The maximum vibration level recorded at this site was 80 VdB. This level represents the maximum vibration level recorded at any site along the entire proposed project corridor. While this level is extremely high, it is explained by the movement of freight trains along the existing CSXT tracks. These tracks are located very close to the apartment buildings where readings were taken.
- Site S20 is representative of a UMD Campus building that would be very close to the proposed Purple Line. While the exterior vibration level of 61 VdB would most likely not be perceptible to humans, the interior level was recorded at 67 VdB. Interior and exterior vibration levels were recorded during similar traffic conditions and therefore, as explained in the FTA Manual and as observed in the UMD Campus building for this monitoring program, the elevated interior vibration level was related to the building’s mechanical systems and/or the movement of people inside. Although the interior vibration measurement was taken on the building’s ground floor, contributions to the elevated vibration may also have come from floor and wall resonances.
- Recorded vibration levels at Sites S22 and S24 were 69 and 71 VdB, respectively. While both monitoring locations were influenced by vehicles traveling along heavily-used roadways, neither location was influenced by an atypical vibration event. The maximum recorded levels for both locations were within the very low frequency range of 10 to 15 Hz. Accordingly, it is likely that at these locations heavy truck or bus traffic was influenced by rough roadways or other roadway anomalies.

Table 7. Measured Maximum Vibration Levels Within Study Area

Site #	Monitoring Location Description	Land Use	Maximum Vibration Level (VdB) (1)
S1	4309 Elm Street	SFR	60
S2	4242 Montgomery Avenue	MFR	50
S3	4230 East West Highway	SFR	56
S4	4104 Edgevale Court	SFR	46
S5	3929 Newdale Road	MFR	38
S6	3607 Chevy Chase Lane	MFR	35
S7	2825 Terrace Drive	MFR	53
S9	1946 Rosemary Hills Drive (Barrington Apartments)	MFR	80
S11	1515 East Falkland Lane (Falkland Apartments)	MFR	50
S12	801 Wayne Street	Recording Studio	61
S14	301 Mansfield Road	SFR	44
S15	8804 Plymouth Street	MFR	57
S16	8831 Arliss Street	SFR	59
S17	8629 Piney Branch Road	MFR	63
S18	727 University Boulevard East	SFR	64
S19	2421 University Boulevard East	SFR	58
S20	Dorchester Hall	UMD Dormitory	67/ 61 (2)
S21	Leonard Town Hall	UMD Dormitory	54
S22	5419 Quintana Street	SFR	69
S23	6002 Eastpine Drive	SFR	58
S24	6751 Riverdale Road	SFR	71
S25	104 Chesapeake Road	MFR	48
S26	4100 Hanson Oaks Dive	SFR	55

Notes: SFR – Single-Family Residence; MFR – Multi-Family Residence
[1] Vibration readings recorded December 5th to 8th 2011. Maximum vibration level for one-third octave band frequencies (5Hz to 100Hz)
[2] Represents vibration readings taken inside/outside of this building. Interior readings were affected by mechanical systems within the building.

3.2.2 University of Maryland Campus Vibration Monitoring

Measured vibration levels within the UMD campus were collected as part of a 2009 study completed at the request of the Maryland Department of Transportation at non-residential buildings within the UMD Campus. The resulting measurements and analysis are in the report *Purple Line Project - University of*

Maryland - Ambient Vibration Study (August 2009), which is included in Appendix F. Vibration levels were measured within various laboratories and research facilities and along exterior portions of buildings in which vibration sensitive equipment has historically been housed and continues to be used. The report indicates that measurements for the 2009 UMD monitoring program were separated into three categories:

- Ambient vibration velocity levels found in the basements and outside grounds of 16 buildings
- The relative relationship, or coupling transmissibility, between the buildings and the outside grounds
- Ambient vibration levels currently affecting UMD's vibration-sensitive devices

The study included vibration measurements inside and outside of 16 buildings and two parking lots, as well as measurements near 30 vibration-sensitive laboratory devices. The measurements were performed for two reasons: 1) to retest and validate the ambient vibration levels reported by Vibro-Acoustics in their *"Campus Vibration and Noise Ambient Environment Report (October 2008)"* sponsored by UMD; and 2) to determine ambient vibration conditions under which various vibration-sensitive devices are currently operating in an acceptable manner.

All vibration measurements were recorded while the classes were still in session. As a result, these readings accurately document the vibration effects resulting from buses and student activity. In addition to performing vibration measurements near sensitive instrumentation, measurements were performed in basements of buildings and on the grounds nearby the buildings. This enabled the report to demonstrate the behavior of the buildings relative to outside ground vibrations. Following is a summary of the results of the 2009 vibration study report:

- The ambient vibration levels measured in third-octave band format from 1 Hz to 100 Hz inside the basements of 16 buildings were similar to the levels reported previously by Vibro-Acoustics.
- When averaged over all 16 buildings, the RMS vibration velocity levels inside the buildings' basements averaged between 7 and 58 micro-inches/second, with the minimum occurring in the 2.5 Hz third-octave band and the maximum occurring in the 10 Hz third-octave band. Levels measured by Vibro-Acoustics averaged from about 5 to 97 micro-inches/second with the same general distribution over the lower third-octave bands but with higher levels reported in the upper bands, particularly in the 31.5 Hz band. Ambient vibration levels at the majority of the monitored locations were below the FTA vibration impact criterion of 42 VdB (125 micro-inches/second) for sensitive devices.
- When comparing average building vibration levels to exterior grounds, the buildings tended to vibrate less than the ground in the third-octave frequency bands below 5 Hz. This pattern is normal and would be expected, given the coupling/transmissibility inefficiencies between the ground and the buildings. The buildings and the outside grounds tended to vibrate coincidently (i.e. the same) within the 5 Hz to 63 Hz bands. However at the higher frequency bands of 63 Hz to 100 Hz, the buildings vibrated more than the outside grounds, indicating that vibration sources inside the buildings themselves were dominating.
- At UMD's vibration-sensitive devices, the vibration velocity levels in the vertical (Z) direction were notably higher than in either the latitudinal (X) or longitudinal (Y) directions. The majority of the vibration levels throughout the 1 Hz to 100 Hz band region tended to range between 10 and 100 micro-inches/second, with several measurement readings elevated by an order of magnitude into the 100 to 1,000 micro-inches/second range in the mid-frequency bands.

For a more detailed discussion regarding the ambient vibration levels at specific UMD campus buildings and for the list of the specific equipment monitored, refer to the *Purple Line Project - University of Maryland - Ambient Vibration Study* (August 2009).

4. Environmental Consequences

4.1 Long-term Operational Effects

Project-related vibration levels were estimated at each of the 23 monitoring sites listed in Table 7 plus three additional locations that were identified as examples of unique building usage that are not represented by the monitoring sites (a large apartment building represented by S10 and school buildings represented by S8 and S13). Project-related details for each site are described in Table 8.

Table 8. Predicted Levels of Ground-Borne Vibration

Site Description	Land Use	Measurement Location	FTA Land Use Category	Train Speed (mph)	Future Distance To Track Midpoint (feet)	FTA Criteria Threshold (VdB)	Estimated Vibration Level (VdB) (1)	Potential Impact
S1	SFR	4309 Elm Street	2	45	110	72	67	No
S2	MFR	4242 Montgomery Avenue	2	45	44	72	73	Yes
S3	SFR	4230 East West Highway	2	45	45	72	74	Yes
S4 (2)	SFR	4110 Edgevale Court	2	45	45	72	74	Yes
S5	MFR	3929 Newdale Road	2	45	115	72	65	No
S6	MFR	3607 Chevy Chase Lane	2	45	55	72	71	No
S7	MFR	2825 Terrace Drive	2	45	60	72	71	No
S8	School	Rosemary Hills Elementary	3	45	60	75	71	No
S9	MFR	1946 Rosemary Hills Drive (the Barrington Apartments)	2	45	22	72	78	Yes
S10	MFR	8600 16th Street (8600 Apartments)	2	39	60	72	71	No
S11	MFR	1515 East Falkland Lane (Falkland Apartments)	2	39	28	72	75	Yes
S12	Studio	801 Wayne Street	NA (3)	10	55	65	58	No
S13	School	Silver Spring International Middle School	3	10	55	75	58	No
S14	SFR	301 Mansfield Road	2	10	70	72	57	No
S15 (2)	SFR	8810 Bradford Road (corner of Plymouth Street) (4)	2	20	65	72	63	No
S16	SFR	8831 Arliss Street	2	20	65	72	63	No
S17	SFR	8629 Piney Branch Road	2	20	60	72	64	No
S18	SFR	727 University Boulevard East	2	19	85	72	61	No
S19	SFR	2421 University Boulevard East	2	35	110	72	63	No

Table 8. Predicted Levels of Ground-Borne Vibration (continued)

Site Description	Land Use	Measurement Location	FTA Land Use Category	Train Speed (mph)	Future Distance To Track Midpoint (feet)	FTA Criteria Threshold (VdB)	Estimated Vibration Level (VdB) (1)	Potential Impact
S20	MFR	Dorchester Hall	2	10	90	72	55	No
S21	MFR	Leonard Town Hall	2	15	50	72	62	No
S22	SFR	5419 Quintana Street	2	32	50	72	68	No
S23	SFR	6002 Eastpine Drive	2	35	68	72	68	No
S24	MFR	6751 Riverdale Road	2	25	45	72	67	No
S25	MFR	104 Chesapeake Road	2	28	65	72	66	No
S26	SFR	4100 Hanson Oaks Dive	2	25	65	72	65	No

Notes: (1) Estimated vibration level includes speed corrections
(2) Vibration assessment locations S4 and S15 are the closest locations to the proposed transitway in the representative area, and thus represent the most conservative assessment location for other vibration receptors in the area. However, the locations were not used to collect vibration monitoring data as site access was not available. For S4 and S15, representative vibration monitoring data was collected at neighboring properties at 4104 Edgevale Court and 8804 Plymouth Street.
(3) Categorized as a special building usage in Table 8-2 of "*Transit Noise and Vibration Impact Assessment*," FTA, 2006.
(4) Based on the predicted vibration level for this location, ground-borne noise from the operation of Purple Line LRT in the proposed Plymouth Street Tunnel would be below the FTA impact criteria presented in Table 2.

Estimated vibration levels at receptor sites 50 feet or greater from the Purple Line transitway ranged from 55 to 71 VdB. For receptors closer than 50 feet, the levels ranged between 67 and 78 VdB at sites S24 and S9 respectively. In most areas, no vibration impact is projected to occur from service operations; however, within 50 feet of the transitway alignment, five receptors (Sites S2, S3, S4, S9, and S11) are predicted to experience project-related vibration levels at or above the FTA 72 VdB impact threshold. Sites S2, S9, and S11 represent three multi-family apartment buildings. Sites S2 and S3 represent two residential neighborhoods. Two single-family residences within each of these neighborhoods are located 45 feet from the track. At that distance the vibration levels would be above the impact threshold. The remaining residences are further from the track and their vibration levels would be below the impact threshold.

Vibration attenuation associated with the foundation coupling and floor to floor loss for typical building structures sometimes reduces the exterior ground-borne vibration experienced inside the building significantly, even when considering the possible vibration amplification from resonant walls, floors and ceilings. Therefore, as shown below in Table 9, a refinement of the vibration assessment was conducted for the impacted properties identified in Table 8 utilizing FTA adjustment factors for foundation coupling loss, floor to floor attenuation, and building resonance gain as they relate to each building type. Applied adjustment factors were based on those shown in Table 1 of this report.

Estimated vibration levels, applying the refined vibration assessment, indicate that with the inclusion of the adjustment factors, two receptor locations would now be below the FTA vibration impact criteria threshold level.

Sites S3 and S4, both located 45 feet from the centerline of the proposed transitway alignment, would experience vibration levels in the range of 73 VdB. Site S9, the Barrington Apartments, would see vibration levels above the FTA impact threshold because of a combination of high existing vibration levels reaching 80 VdB associated with 30 CSXT freight train movements, with Purple Line operations adding 70 more pass-by events per day. The vibration levels caused by Purple Line movements are expected to reach 72 VdB at this site.

Table 9. Predicted Levels of Ground-Borne Vibration with Adjustment Factors Included

Representative Site Name	Land Use	Measurement Location	Predicted Vibration Level with Adjustments (VdB) (1)	Impacts	Amount Over FTA Criteria Level (VdB)	Total Number Of Affected Properties
S2	MFR	4242 Montgomery Avenue	67	No	-	1 MF
S3	SFR	4230 Montgomery Avenue	73	Yes	1	2 SF
S4	SFR	4110 Edgevale Court	73	Yes	1	2 SF
S9	MFR	1946 Rosemary Hills Drive (the Barrington Apartments)	72	Yes (2)	-	1 MF
S11	MFR	1515 East Falkland Lane (Falkland Apartments)	69	No	-	1 MF

Notes: (1) Results include FTA vibration adjustment factors for foundation coupling loss, floor to floor attenuation, and building resonance gain; (2) For the Barrington Apartments, vibration impacts would exist regardless of the predicted vibration level.

The ground-borne noise generated from operating the Purple Line operations in the proposed Plymouth Street tunnel is predicted to be 28 dBA, which would be below the applicable FTA impact criteria.

A detailed study of extremely sensitive equipment is not a part of the general vibration assessment conducted for this report. However, based on a current agreement between MTA and UMD, acceptable vibration impact criteria for sensitive buildings to be applied to the project shall include the greater of the ambient vibration levels at sensitive research laboratories or the NIST-A criteria within 100 feet of the nearest track centerline at existing and potential research laboratories. Potential research laboratories on the UMD Campus that would be within 100 feet of the proposed transitway centerline include HJ Patterson Hall and the Microbiology Building. Utilizing the generalized vibration curves shown in Figure 2, the future service operations of the Purple Line are predicted to cause vibration impacts for these two buildings. In addition, based on the monitored vibration levels contained in the “*Purple Line Project - University of Maryland - Ambient Vibration Study* (August 2009),” other extremely sensitive UMD Campus buildings located farther than 100 feet from the track centerline currently operate under extremely low levels of vibration. Therefore, a more detailed assessment of vibration for these two sensitive buildings, which would take into consideration the specific frequency characteristics of the vibration created by the Purple Line LRT along with individual building response, soil propagation characteristics and building coupling effects, should be conducted as the project design advances. Once a more accurate determination of all vibration impacts is made, appropriate mitigation measures can be developed, in coordination with UMD.

4.1.1 Potential Mitigation Measures

For the proposed Purple Line project, vibration impacts are projected to occur at a total of three monitoring locations. These locations, shown in Table 9, include four single-family homes (represented by S3 and S4) and the Barrington Apartments (S9). The four single-family properties are representative of areas where the estimated vibration levels would surpass the FTA vibration impact criteria. Also included in the table is the amount by which the FTA vibration criteria are surpassed at each of these two single-family locations. The third impacted property, the Barrington Apartments, is represented by Site S9. Impacts related to this property would be the result of the combination of two issues: 1) high existing levels of vibration from nearby freight train movements that are presently above the FTA vibration impact criteria, with measured levels of 80 VdB, as indicated in Table 7 and 2) the daily number of projected Purple Line LRT trains, which would more than double the number of existing daily freight trains. As a result, mitigation recommendations for the Barrington Apartments are discussed separately from the two single-family homes.

The goal of vibration mitigation would be to reduce the amount of vibration at impacted residential properties to below the FTA 72 VdB criteria level. Since the project would be new construction, the most appropriate type of mitigation would likely include upgrades to the proposed track support system. This type of mitigation could include the following elements:

- *Resilient Fasteners*: Standard rail fasteners are typically used to attach the rail to the support structure. However, the standard fasteners are very stiff in the vertical direction, thus increasing vibration levels. Resilient fasteners significantly reduce this stiffness such that vibration levels could be reduced by 5 to 10 VdB and thereby effectively reduce projected vibration levels adjacent to Sites S3 and S4.
- *Ballast Mats*: A ballast mat consists of a rubber (such as shredded rubber tires), cork or other type of resilient elastomer pad that is placed under the normal ballast, ties, and rail. The ballast mat would be placed on a concrete or asphalt layer to be most effective. Ballast mats can provide 5 to 12 VdB attenuation at frequencies above 25 to 30Hz.
- *Resiliently Supported Ties (Under-Tie Pads):* This treatment consists of resilient rubber pads attached underneath concrete ties in ballast. Some measurement data suggest that resiliently supported ties may reduce low frequency vibration in the 15 to 40 Hz range, which would make them particularly appropriate for rail systems with vibration issues in the 20 to 30 Hz range.

Current operations of the CSXT freight line result in existing vibration levels above the impact criteria at the Barrington Apartments. According to the FTA guidance manual, additional impact from the proposed project would result if the number of projected events would more than double the existing CSXT freight traffic. Based on the assumed Preferred Alternative LRT headways, the project would more than double the daily number of train pass-by events. As a result, mitigation options would need to center on reducing the rail vibration created by the proposed LRT trains to levels below the FTA vibration impact criteria. Potential mitigation options could include those described above for the two single–family buildings. However, these mitigation measures would be limited to the Purple Line tracks, and therefore none of these mitigation measures would reduce in any way vibration presently generated from the freight train movements.

4.1.2 Mitigation

MTA will perform site-specific assessments of those areas identified in the FEIS as having potential vibration impacts. MTA will develop appropriate mitigation measures.

MTA will analyze extremely vibration-sensitive buildings located within the UMD campus, as agreed upon by MTA and UMD. The study will establish criteria, and measure regarding mitigation for vibration will be specified in the MTA UMD agreement (a draft of which is included in Appendix E). MTA will develop appropriate mitigation measures.

4.2 Short-term Construction Effects

Constructing the Purple Line would involve a range of activities, including excavating the rail right-of-way, tunnel construction, constructing grade crossings, bridges and the yard and maintenance facilities, laying track, constructing stations and other system elements, and the movement of heavy trucks and construction equipment. The potential for vibration impacts to occur is low for construction activities which utilize equipment such as air compressors, rubber wheeled vehicles, hydraulic loaders and other light equipment usage. However, some specialized construction work does have the potential to create vibration impacts: tunneling, pile driving, and heavy equipment use.

The location of sensitive receptors in relation to the construction activity and the duration of construction activities affect the potential for vibration impact. These factors are described below. Estimates of potential impact are preliminary and subject to reassessment by the MTA when the MTA develops its construction plan for the Preferred Alternative. MTA expects relatively small areas of the proposed project corridor to experience vibration effects from construction activities at any given time. Track-related construction would move continuously along the corridor; therefore, the duration of potential exposure to construction-related vibration at any one property would be limited.

A potential does exist, however, for vibration-sensitive buildings to be impacted by non-track related types of construction. Examples include construction of the Silver Spring Transit Center, the Plymouth Street Tunnel, and sections along the transitway where extensive bridge and retaining wall work would occur. However, the impact would be realized only for sensitive receptors in close proximity to these specific locations and not along the entire length of the transitway.

Construction of the Plymouth Street tunnel, which potentially would include blasting, is expected to be the longest sustained period of construction, and blasting typically would generate the most vibration. While overall construction of the tunnel would last approximately 30 months, the anticipated duration of the blasting operations, if any, would be substantially less.

Other locations where heavy construction would occur for extended periods of time are the Silver Spring Transit Center and associated structures and the Rock Creek and Lyttonsville Place bridges. Although heavy construction activities would be occur at all three of these locations, no vibration sensitive receptors are present in close proximity to these proposed construction sites.

Certain construction activities, such as pile driving for new structures and retaining walls, would occur at numerous locations along the corridor and have the potential to create more vibration than other activities. The methods for driving the piles would include both impact and non-impact procedures. Preliminary engineering indicates that the following sensitive receptors would be in close proximity to pile driving: the Falkland Chase Apartments, Rosemary Hills Elementary School, and the Barrington Apartments.

Table 10 shows the damage impact distances for some typical construction activities for residential Category III buildings (i.e. non-engineered timber and masonry buildings). The distances presented in Table 10 for potential damage are based on the construction-related vibration source levels shown in Table 5, and the FTA's construction vibration damage criteria. Beyond these distances, damage to buildings from the specified equipment is unlikely. However, estimates of potential impact are preliminary and subject to reassessment by the MTA during Final Design when the MTA develops its construction plan for the Preferred Alternative.

Table 10. Distance to Potential Construction Damage for Residential Buildings

Equipment Type	Distance to Potential Damage (feet) (1) (2)
Vibratory Roller	25
Caisson Drilling	15
Pile Driver (Impact)	55
Pile Driver (Vibratory)	22
Jackhammer	8
Bulldozer	15

Notes: (1) Based on a damage criteria of 0.2 PPV inches per second for fragile buildings and 0.12 inches per second for extremely fragile historic buildings; (2) Results based on vibration damage equation in Section 12.2.1 of the *Transit Noise and Vibration Impact Assessment*, FTA, 2006.

4.2.1 Avoidance and Minimization

MTA will identify control measures to be implemented by the contractor during construction activities to minimize the potential for vibration impacts.

As the project design advances, MTA will consider requiring that the construction contractor employ the following control measures to minimize the potential for vibration impacts during construction:

- Notify the community of all blasting operations well before the activities commence
- Schedule blasting or pile driving activities during hours that would least impact residents at sensitive receptors
- Divert heavy truck and construction equipment movements away from sensitive receptors by utilizing roadways that contain a limited number of residential or sensitive structures
- Hire a Blasting Consultant with adequate experience in performing controlled blasting.
- Set vibration limits for blasting.
- Monitor the vibration of each blast.
- Conduct test blasts prior to full production blasts. These test blasts will allow the Contractor to determine if their proposed blasting methodology is appropriate and meets the vibration requirements prior to completing a full blast.
- Conduct pre-construction survey and post-construction survey in sensitive areas.

4.2.2 Mitigation

Vibration-related effects will be addressed in advance of, or in conjunction with, the construction of the Preferred Alternative. Mitigation is not anticipated to be required.

5. References

Federal Transit Administration (FTA*). Transit Noise and Vibration Impact Assessment*. U.S. Department of Transportation Report No. FTA-VA-90-1003-06, May 2006.

Transit Cooperative Research Program (TCRP). *Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit*. Transportation Research Board, December 2009.

Purple Line Project – University of Maryland – Ambient Vibration Study, August 2009.

M. Sanayei, C. R. Brett, J. A. Zapje, E. E. Unger, E. M. Hines - *Predicting Train-Induced Vibrations in Multi-Story Buildings*, 2008 ASCE.

Eric E Ungar, Douglas H. Sturz, C. Hal Amick – *Vibration Control Design of High Technology Facilities*, July 1990.

Hugh J. Saurenman, James T Nelson, George P. Wilson – *Handbook of Urban Rail Noise and Vibration Control*, UMTA-MA-06-0099-82-1, DOT-TSC-UMTA-81-72, February, 1982.

Colin G. Gordon, *Generic Vibration Criteria for Vibration-Sensitive Equipment*, September 1999.

Appendix A – List of Acronyms and Abbreviations

APPENDIX A

List of Acronyms and Abbreviations

DC	Washington, DC
EMI	Electromagnetic Interference
FEIS	Final Environmental Impact Statement
FTA	Federal Transit Administration
GBN	Ground-Borne Noise
GBV	Ground-Borne Vibration
Hzhertz	Hertz
ICP	Integrated circuit piezoelectric
IEST	Institute of Environmental Sciences and Technology
LRT	Light Rail Transit
MARC	Maryland Area Regional Commuter
MDOT	Maryland Department of Transportation
MTA	Maryland Transit Administration
MWCOG	Metropolitan Washington Council of Governments
NEPA	National Environmental Policy Act
NIST	National Institute of Standards and Technology
PPV	Peak Particle Velocity
RMS	Root Mean Square
SSTC	Silver Spring Transit Center
SHA	State Highway Administration
UMD	University of Maryland
VdB	RMS vibration velocity level, decibels
WMATA	Washington Metropolitan Area Transit Authority

Appendix B – Glossary/Terminology

APPENDIX B

Glossary/Terminology

Accelerometer: A transducer that converts vibratory motion to an electrical signal proportional to the acceleration of that motion.

At-grade: a junction at which two or more transport axes cross at the same level (or grade).

Below-grade: recessed below ground level

Capital Crescent Trail: the existing paved trail between Bethesda and Georgetown. When the trail alongside the Purple Line is built, the Capital Crescent Trail will extend all the way from Silver Spring to Georgetown.

Criteria: Plural form of "criterion," the relationship between a measure of exposure (e.g., sound or vibration level) and its corresponding effect.

Frequency: The number of times that a periodically occurring quantity repeats itself in a specified period with reference to noise and vibration signals, the number of cycles per second.

Grade crossing: The point where a rail line and a motor vehicle road intersect.

Integrated circuit piezoelectric: ICP identifies sensors that incorporate built-in, signal-conditioning electronics

Maryland Area Regional Commuter: a regional/commuter rail system consisting of three lines in the Baltimore-Washington Metropolitan Area

Maryland Transit Administration: the state-operated mass transit administration in Maryland; part of the Maryland Department of Transportation

Metropolitan Washington Council of Governments: a regional organization of consisting of 21 local governments in the Washington Metropolitan Area, as well as members of the Maryland and Virginia state legislatures, the US Senate, and the US House of Representatives

Metrorail: the rapid transit system in Washington, DC, and its surrounding suburbs

Mitigation: efforts to reduce or compensate for adverse impacts

National Environmental Policy Act: a United States environmental law that established a national policy promoting the enhancement of the environment; also established the President's Council on Environmental Quality (CEQ)

No Build: the baseline against which the environmental and community impacts of the Preferred Alternative are compared; consists of the transit service levels, highway networks, traffic volumes, and demographics forecasted for horizon year 2040

One-third octave band: A standardized division of a frequency spectrum in which the octave bands are divided into thirds for more detailed information. The interval between center frequencies is a ratio of 1.25

Preferred Alternative: the build alternative that is studied in detail in the FEIS (this alternative is a modified/refined/updated version of the Locally Preferred Alternative)

Purple Line corridor: the general area between Bethesda and New Carrollton

Resonance frequency: The phenomenon that occurs in a structure under conditions of forced vibration such that any change in frequency of excitation results in a decrease in response

Right-of-way: legally granted access for the use of property

Study area: the geographic extent that is examined to assess impacts

Transit Center: a sheltered waiting area where multiple mass transportation routes converge; there are two on the alignment, the Silver Spring Transit Center and the Takoma/Langley Transit Center

Vibration: An oscillation wherein the quantity is a parameter that defines the motion of a mechanical system.

Vibration Velocity Level (L_V): Ten times the common logarithm of the ratio of the square of the amplitude of the RMS vibration velocity to the square of the amplitude of the reference RMS vibration velocity. The reference velocity in the United States is one micro-inch per second, also written as VdB.

Appendix C – Instrument Calibration Certificates

CRYSTAL instruments

4699 Old Ironsides Dr., Suite 100
Santa Clara, CA 95054, USA
Phone: (408) 986-8880
Fax: (408) 834-7818
E-Mail: sales@go-ci.com
Website:www.go-ci.com

CERTIFICATE OF CALIBRATION

Manufacturer:
Crystal Instruments
4699 Old Ironsides Dr., STE.100
Santa Clara, CA 95054
Phone: 408--986-8880

Cal Date: 11/29/2011 **Cal Date File: Cal_41142.dat**
Due Date: 11/29/2012 **Cal Report File: Cal_41142.txt**
Cal Int: 12 Mo.

INSTRUMENT/ID

Model: CoCo-80 **Serial No: 41142**
Description: Dynamic Signal Analyzer
CALIBRATION CONDITIONS
Certified: In Tolerance **Cal Spec: Manufacturer**
Cal'd At: Crystal Instruments
Cal Procedure: CI User's Manual (Version1.0)

CALIBRATION EQUIPMENT USED

Serial Number	Manufacturer	Model No.	Calib.Date	Due Date	Traceability Cert.No.
6966078	FLUKE	45	02/17/2011	02/17/2012	8229-1

REMARKS/COMMENTS
Crystal Instruments certifies that all calibration has been performed using standards whose accuracies are traceable to the National Institute of Standards and Technology. Alternatively, accuracies have been derived from accepted values of natural physical constants, or have been derived by the ratio of self-calibration techniques. This certificate applies only to the instrument identified above and shall not be reproduced, except in full, without the specific written approval by the calibration organization issuing this report.

TECHNICIAN: ______ **QC:** ______

Crystal Instruments Corporation. Phone: 408--986-8880. E-Mail: sales@go-ci.com. http://www.go-ci.com

~ *Calibration Certificate* ~

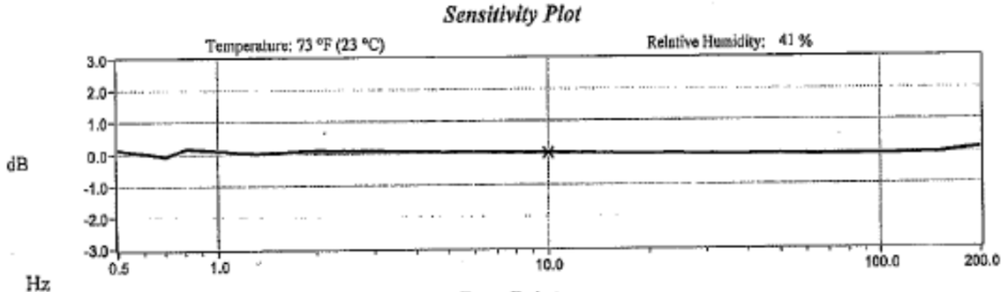
Per ISO 16063-21

Model Number:	393B31		
Serial Number:	32004		
Description:	ICP® Accelerometer	Method:	Back-to-Back Comparison (AT401-12)
Manufacturer:	PCB		

Calibration Data

Sensitivity @ 10.00 Hz	9.65	V/g	Output Bias	11.5	VDC
	(0.984	V/m/s²)	Transverse Sensitivity	0.8	%
Resonant Frequency	881	Hz			

Sensitivity Plot



Data Points

Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)	Frequency (Hz)	Dev. (%)
0.5	1.5	7.0	0.2	50.0	-0.6
0.7	-0.8	REF. FREQ.	0.0	100.0	-0.9
1.0	1.1	15.0	-0.3	200.0	1.2
2.0	1.1	20.0	-0.6		
5.0	0.4	30.0	-0.7		

Mounting Surface: Stainless Steel Fastener: Stud Mount Fixture Orientation: Vertical
Acceleration Level (pk)[1]: 0.100 g (0.981 m/s²)[2]
[1]The acceleration level may be limited by shaker displacement at low frequencies. If the listed level cannot be obtained, the calibration system uses the following formula to set the vibration amplitude: Acceleration Level (g) = 0.133 x (freq)².
[2]The gravitational constant used for calculations by the calibration system is: 1 g = 9.80665 m/s².

Condition of Unit

As Found: n/a

As Left: New Unit, In Tolerance

Notes

1. Calibration is traceable to one or more of the following; PTB 10065, PTB 10066 and NIST 681/280472.
2. This certificate shall not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.
3. Calibration is performed in compliance with ISO 9001, ISO 10012-1, ANSI/NCSL Z540-1-1994 and ISO 17025.
4. See Manufacturer's Specification Sheet for a detailed listing of performance specifications.
5. Measurement uncertainty (95% confidence level with coverage factor of 2) for frequency ranges tested during calibration are as follows: 0.5-0.99 Hz; +/- 1.8%, 1-30 Hz; +/- 1.0%, 30.01-199 Hz; +/- 1.5%, 200-1 kHz; +/- 3.0%.

Technician: Marguerite Alston *MA* Date: 06/16/11

ACCREDITED
CALIBRATION CERT #1862.02

PCB PIEZOTRONICS
VIBRATION DIVISION
Headquarters: 3425 Walden Avenue, Depew, NY 14043
Calibration Performed at: 10869 Highway 903, Halifax, NC 27839
TEL: 888-684-0013 · FAX: 716-685-3886 · www.pcb.com

PAGE 1 of 2

CAL# - 3391075976.64

~ Calibration Certificate - Phase ~

Per ISO 16063-21

Model Number: 393B31

Serial Number: 32004

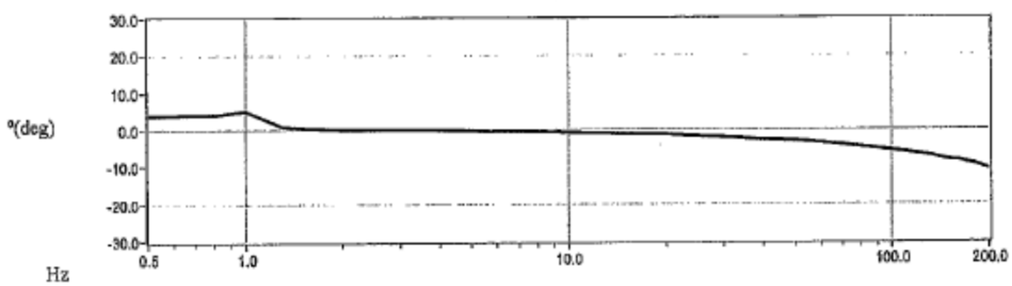
Description: ICP® Accelerometer Method: Back-to-Back Comparison (AT401-12)

Manufacturer: PCB

Calibration Data

[1]Sensitivity @ 10.00 Hz 9.65 V/g (0.984 V/m/s²)

Phase Plot



Data Points

Frequency (Hz)	Phase (°)	Frequency (Hz)	Phase (°)
0.5	3.7	20	-1.3
0.7	4.0	30	-2.1
1.0	5.0	50	-3.0
2.0	-0.0	100	-5.7
5.0	-0.3	200	-10.8
7.0	-0.5		
REF. FREQ.	-0.7		
15	-1.2		

Notes

1. Calibration is traceable to one or more of the following; PTB 10065, PTB 10066 and NIST 681/280472.
2. This certificate shall not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.
3. Calibration is performed in compliance with ISO 9001, ISO 10012-1, ANSI/NCSL Z540-1-1994 and ISO 17025.
4. See Manufacturer's Specification Sheet for a detailed listing of performance specifications.
5. Measurement uncertainty (95% confidence level with coverage factor of 2) for frequency ranges tested during calibration are as follows: 0.5-0.99 Hz; +/- 1.8%, 1-30 Hz; +/- 1.0%, 30.01-199 Hz; +/- 1.5%, 200-1 kHz; +/- 3.0%.

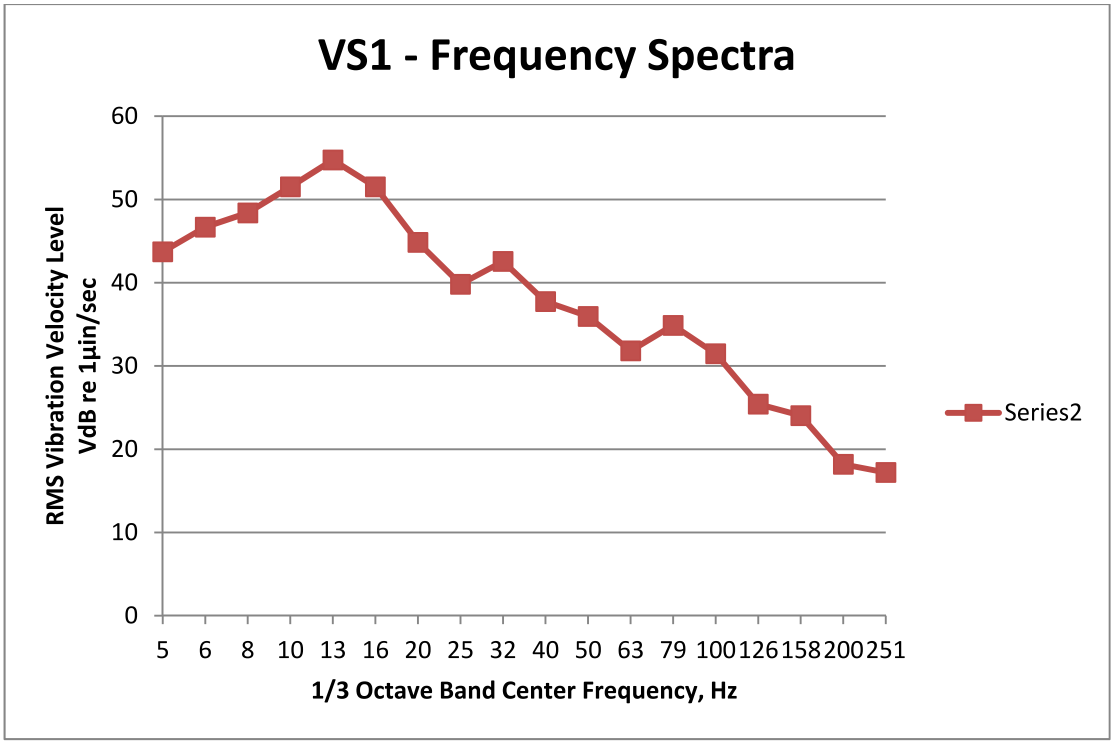
Technician: Marguerite Alston MA Date: 06/16/11

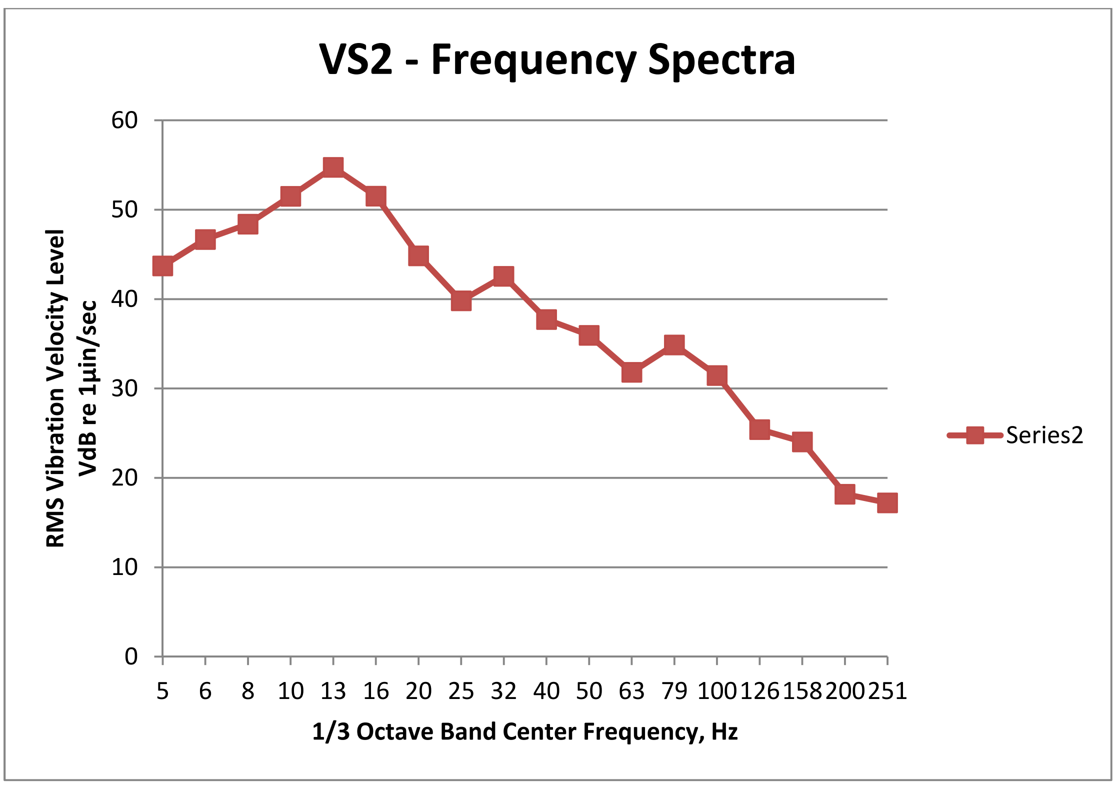
PCB PIEZOTRONICS™
VIBRATION DIVISION

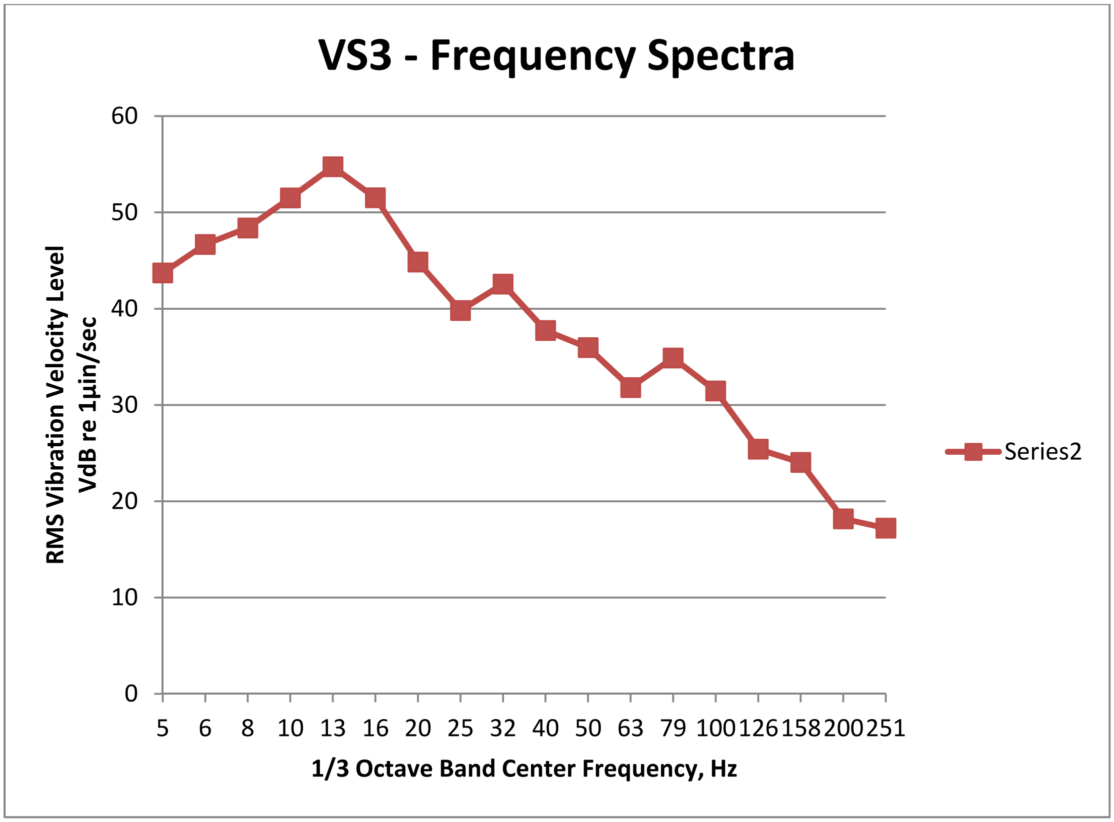
Headquarters: 3425 Walden Avenue, Depew, NY 14043
Calibration Performed at: 10869 Highway 903, Halifax, NC 27839
TEL: 888-684-0013 · FAX: 716-685-3886 · www.pcb.com

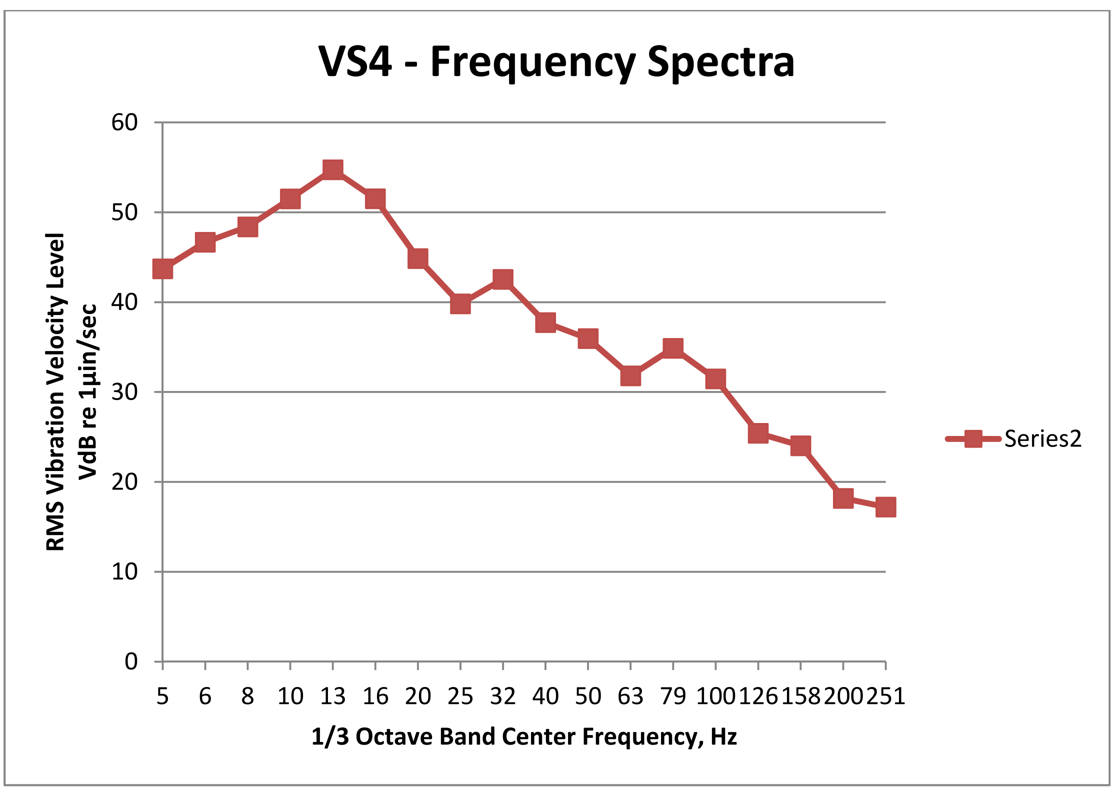
PAGE 2 of 2

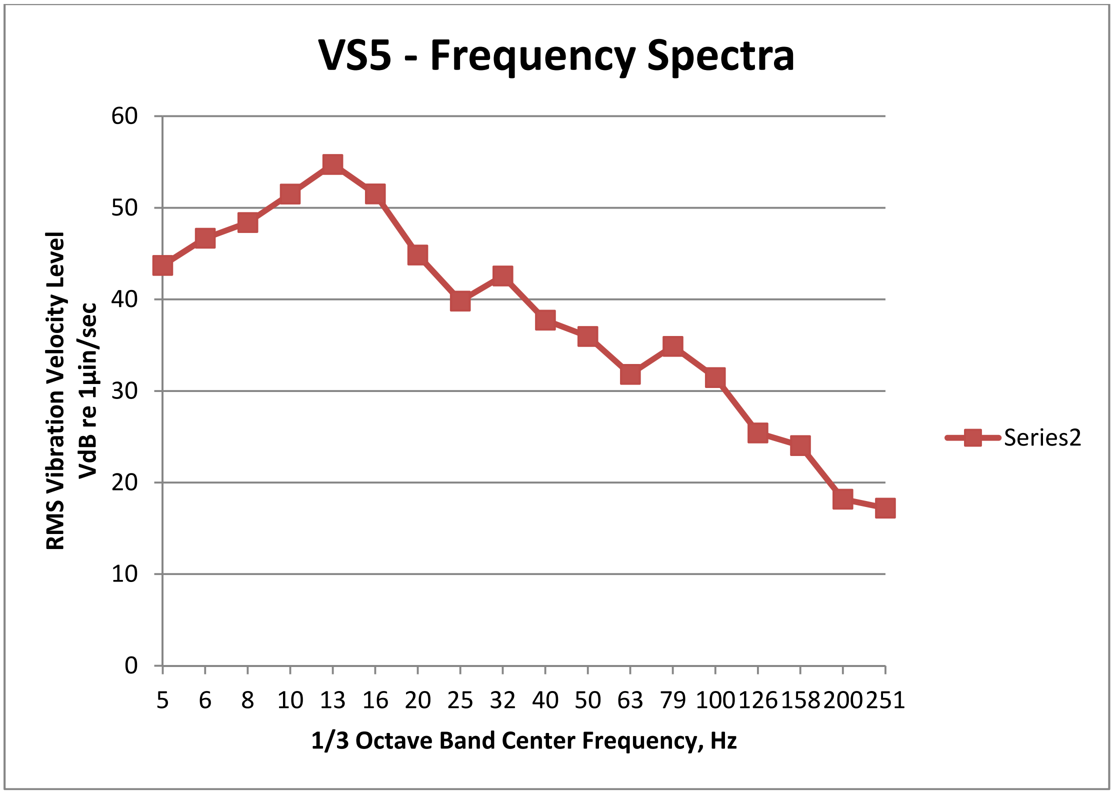
Appendix D – Vibration Monitoring Frequency Spectra

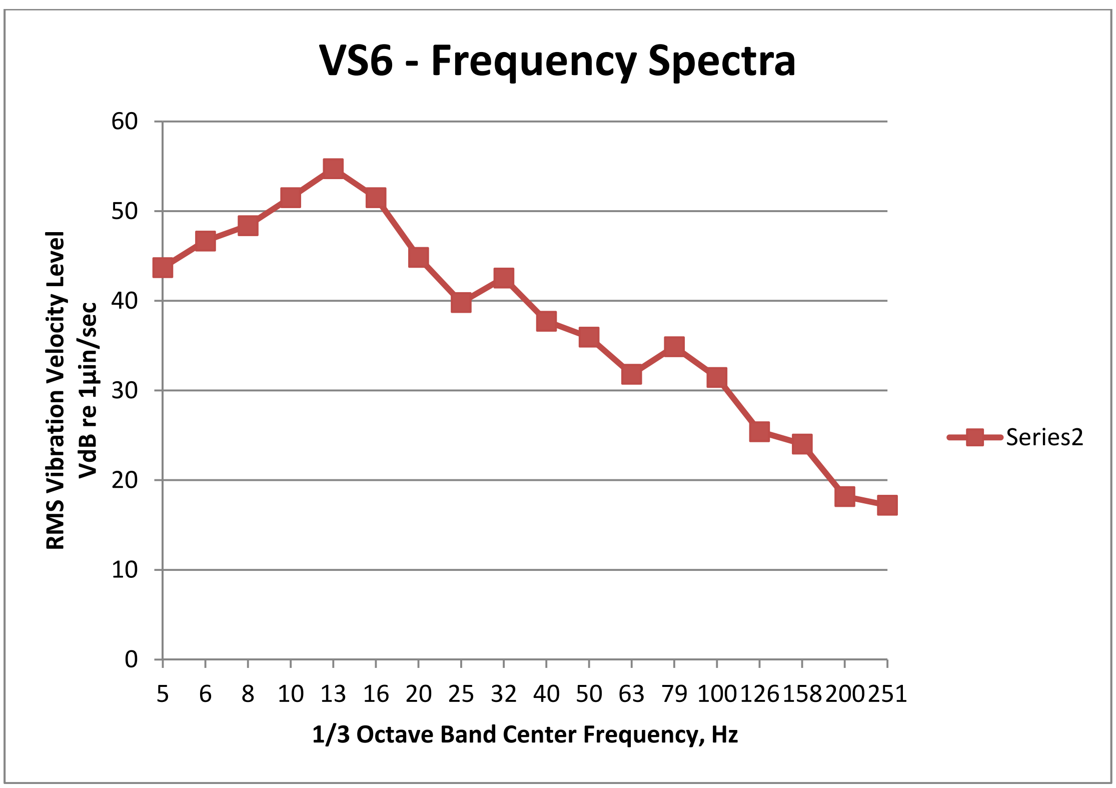

VS1 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

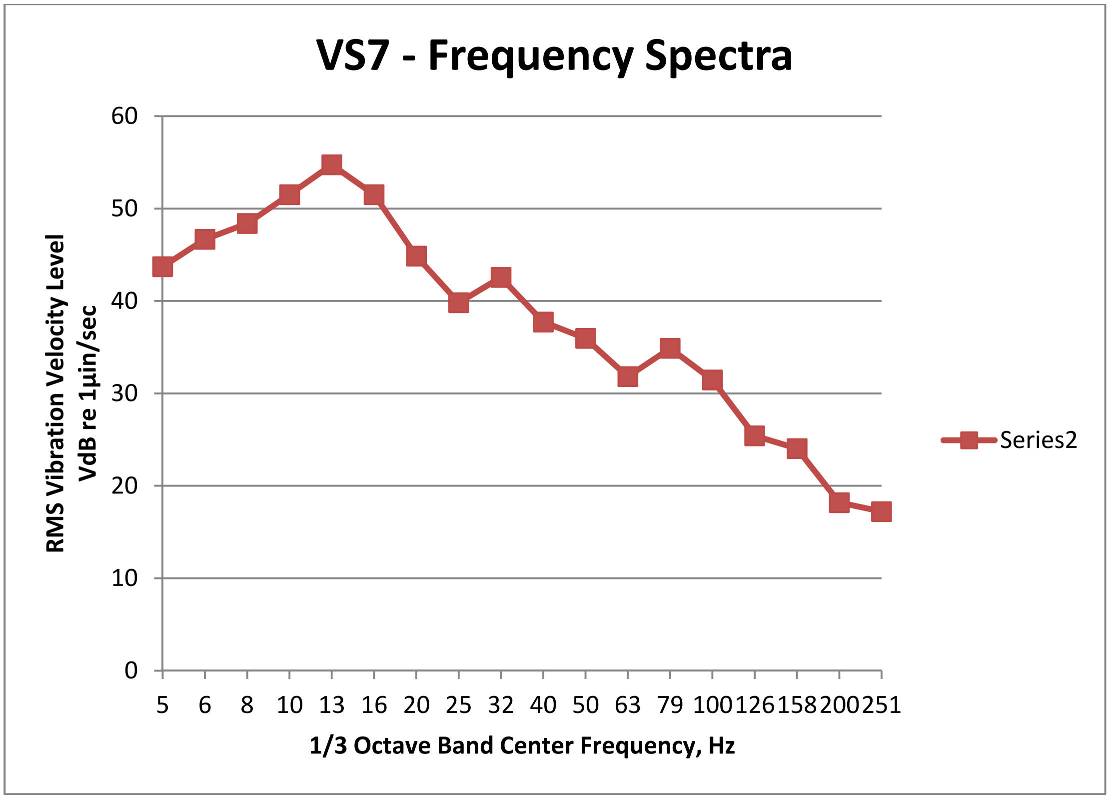

VS2 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

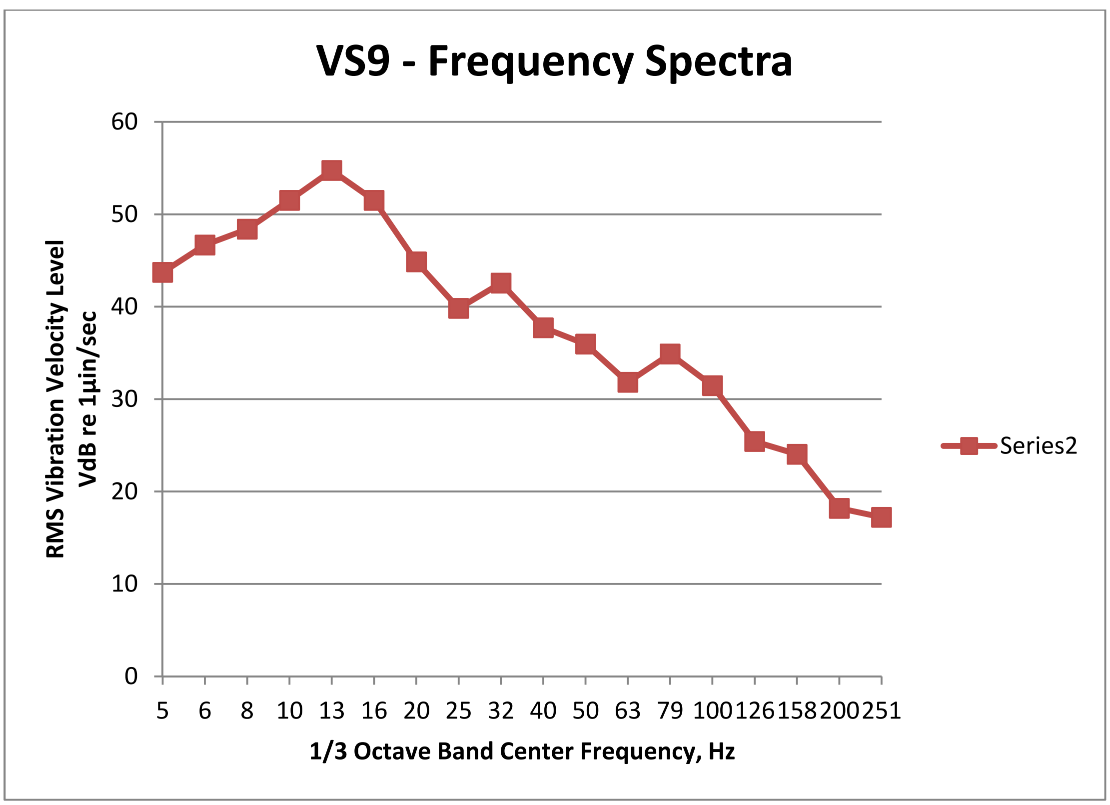

VS3 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

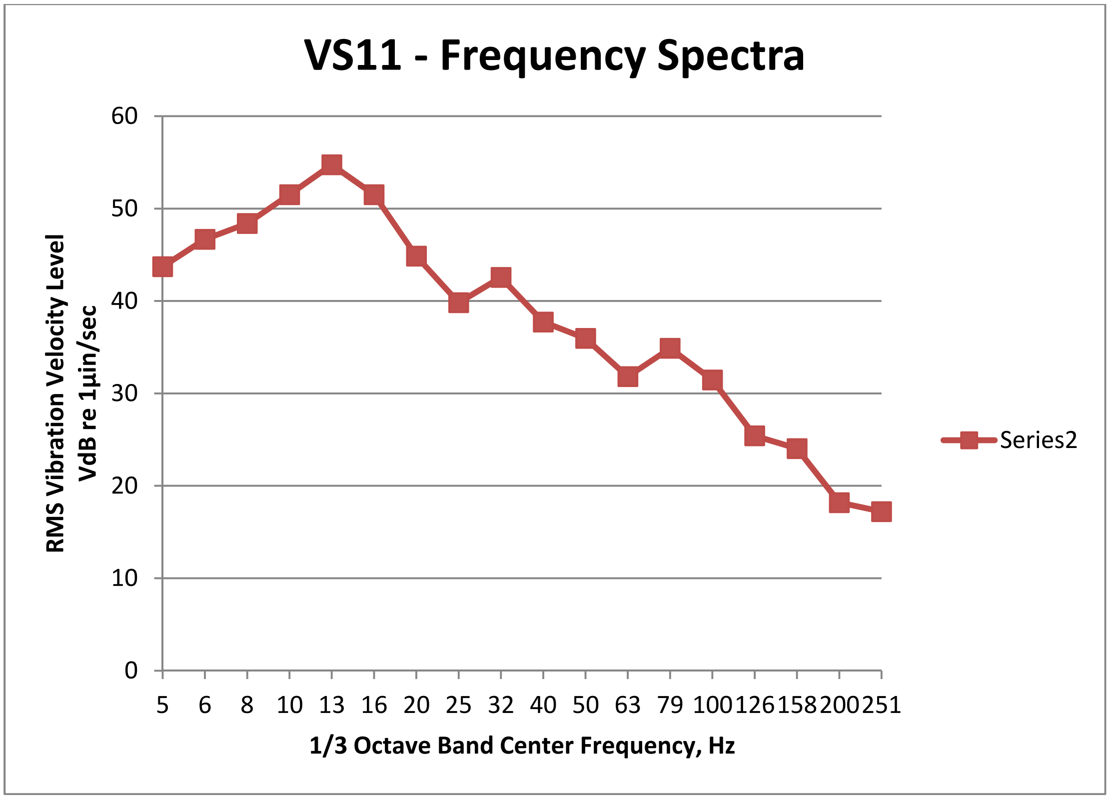

VS4 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

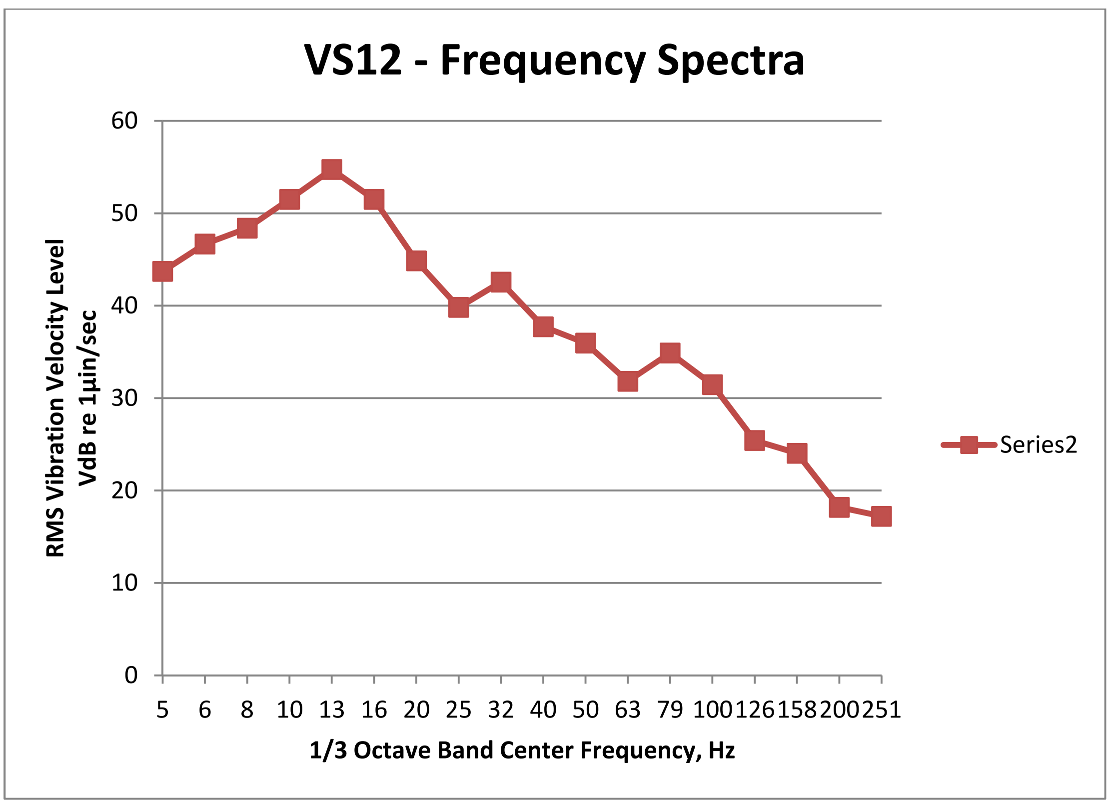

VS5 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

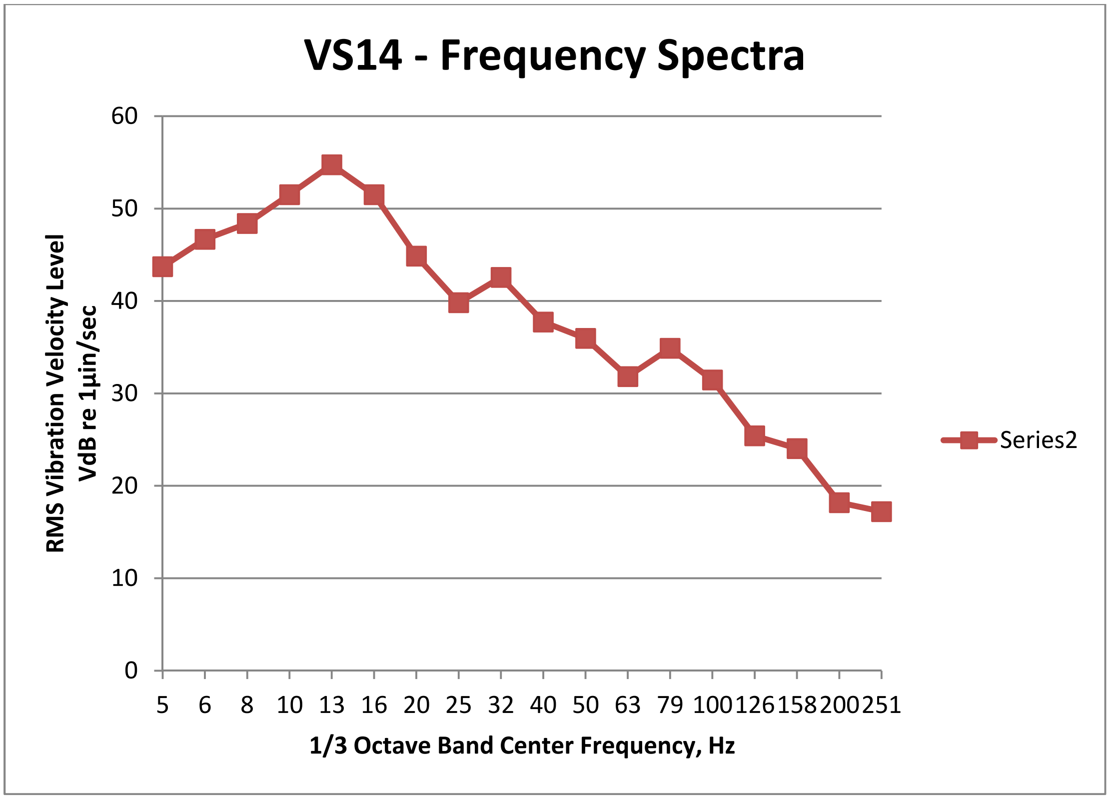

VS6 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

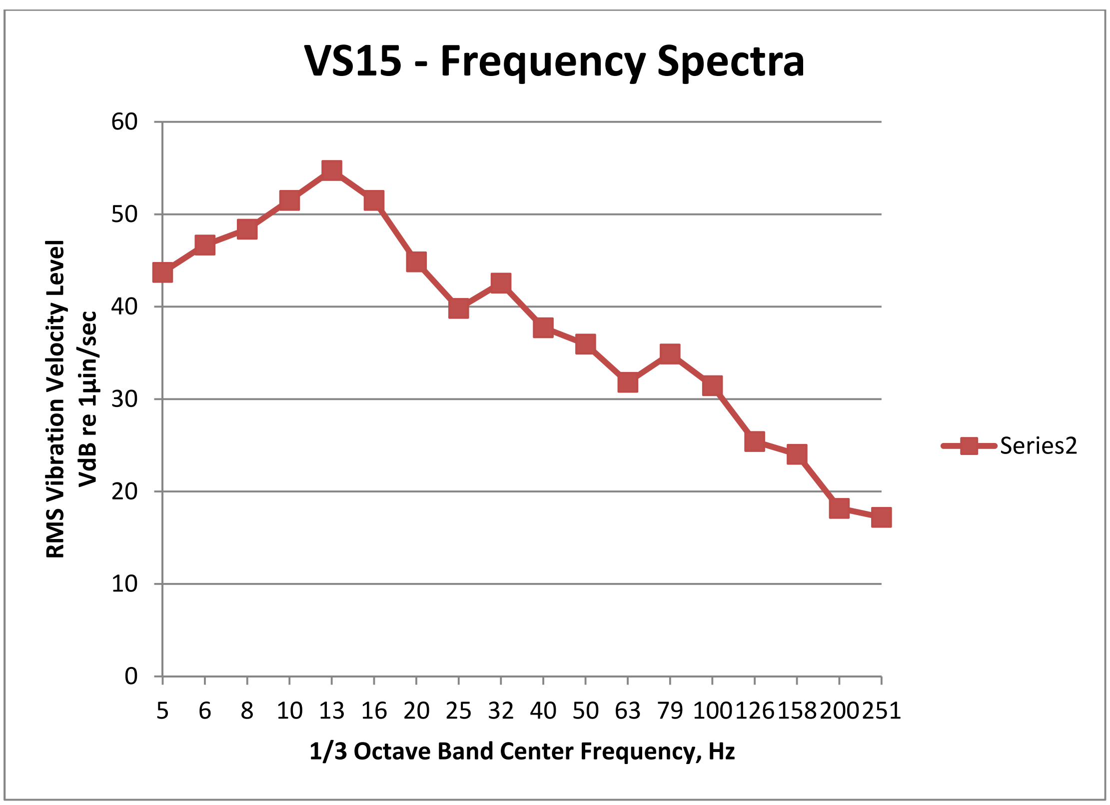

VS7 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
0
10
20
30
40
50
60
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

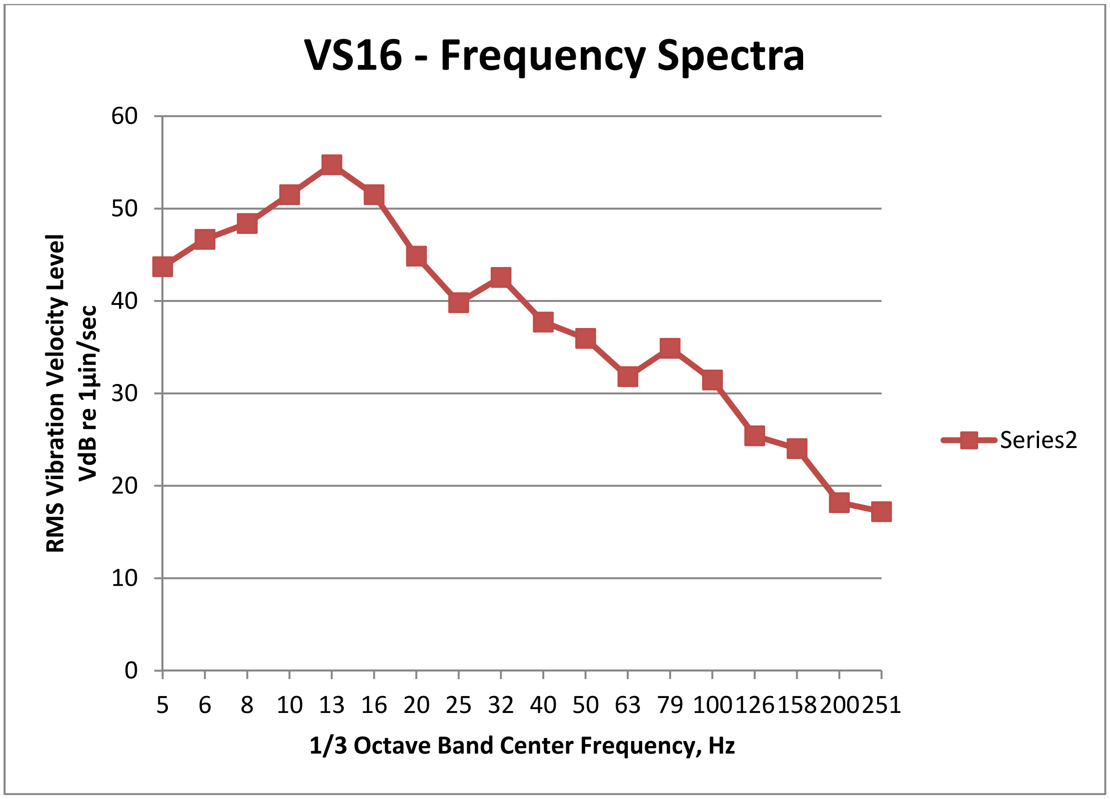

VS9 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
0
10
20
30
40
50
60
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

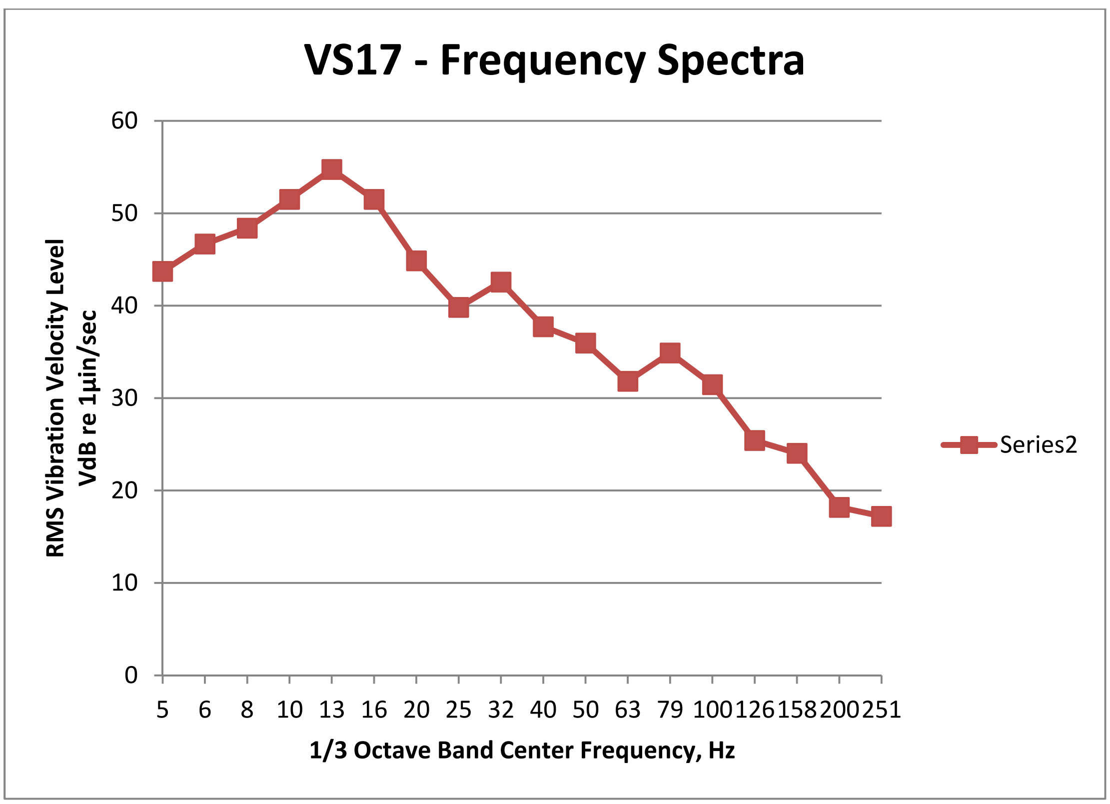

VS11 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

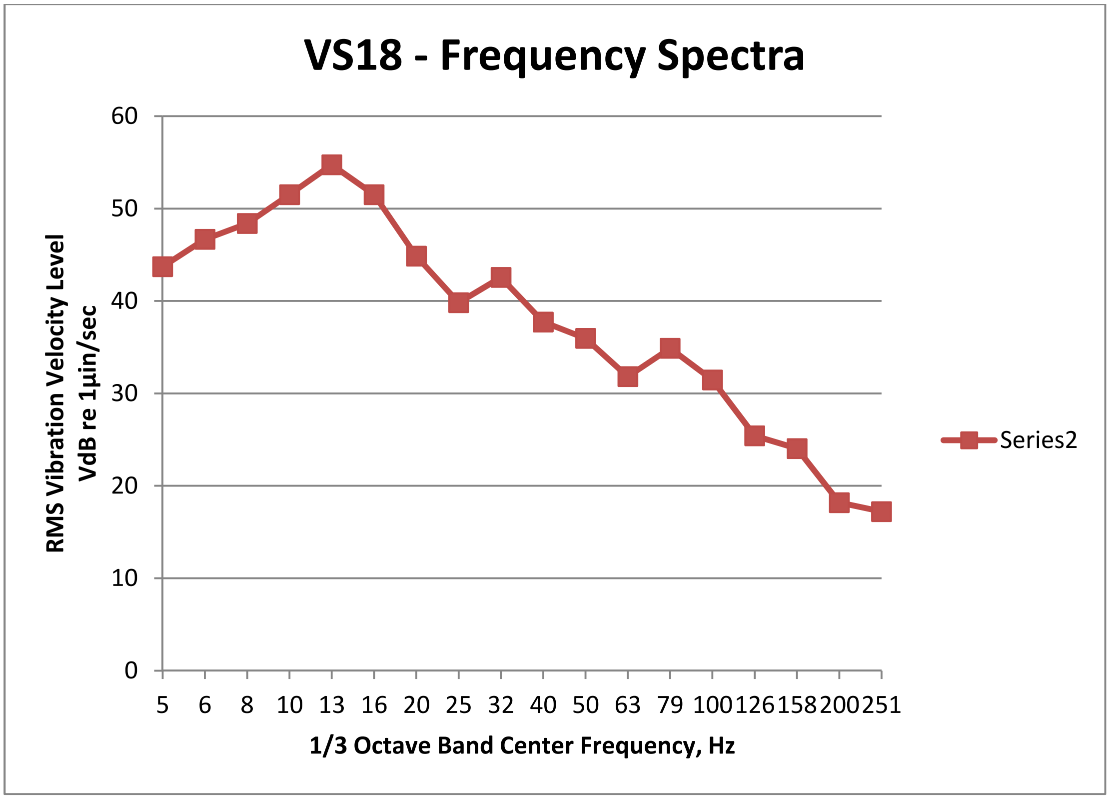

VS12 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

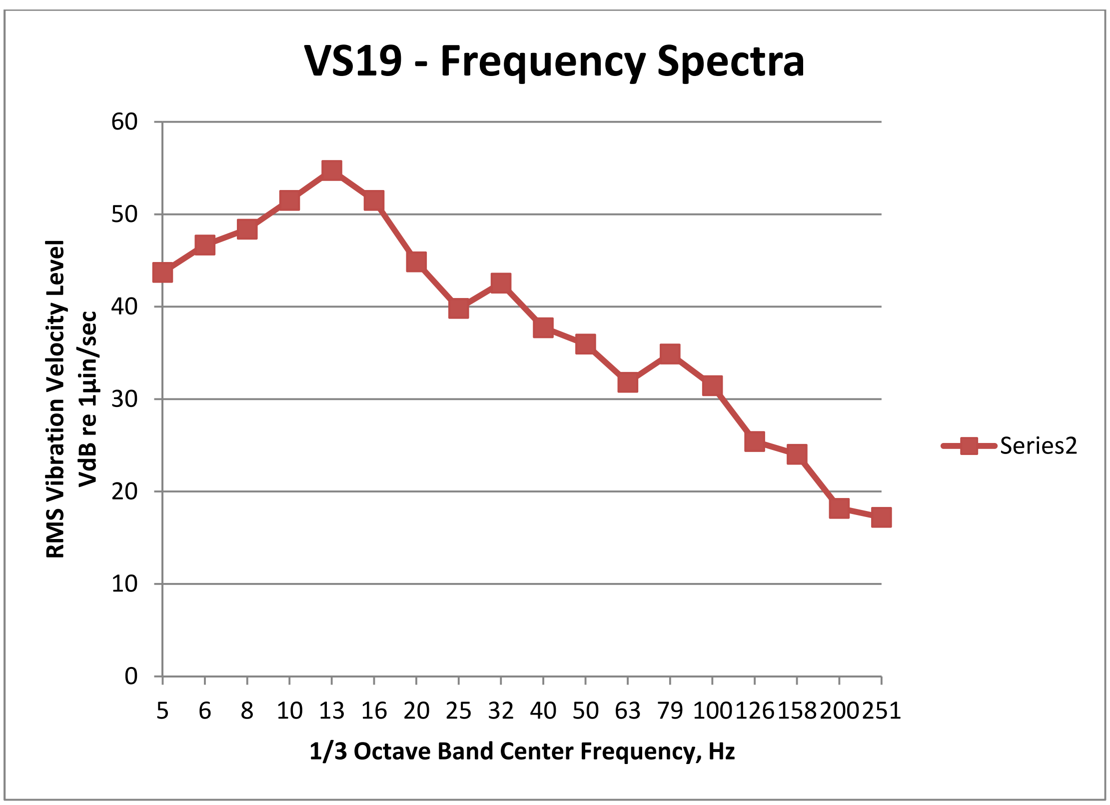

VS14 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

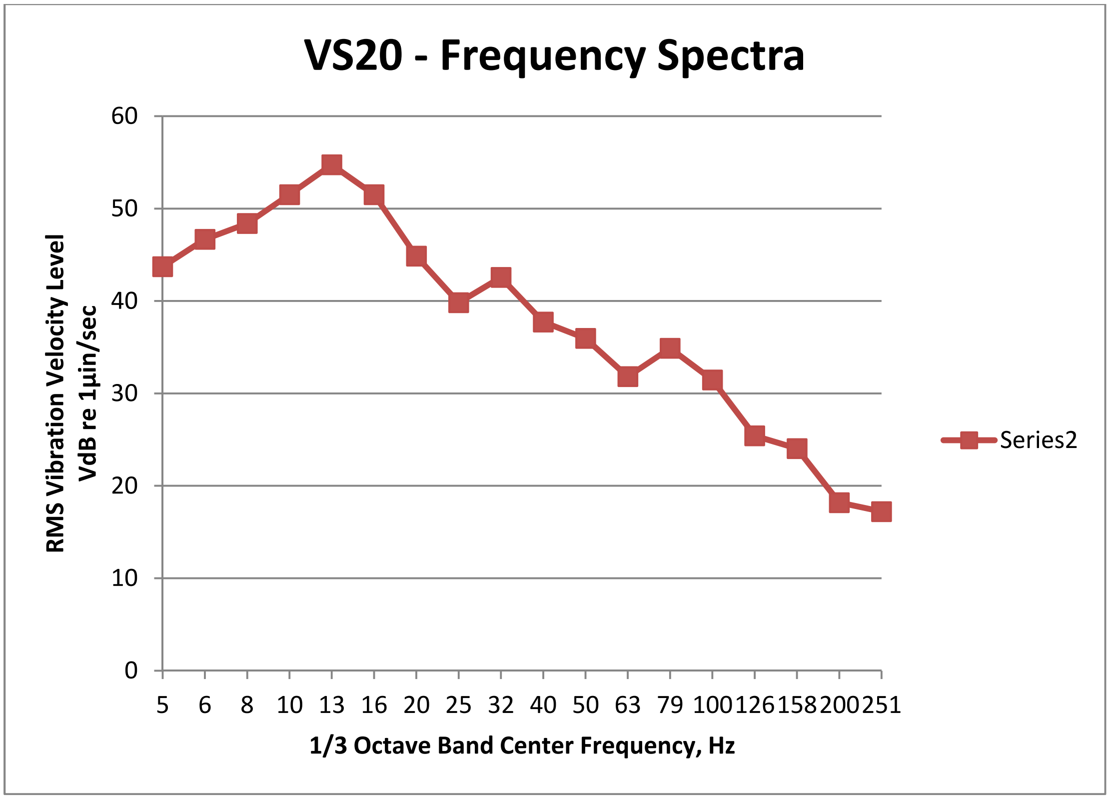

VS15 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

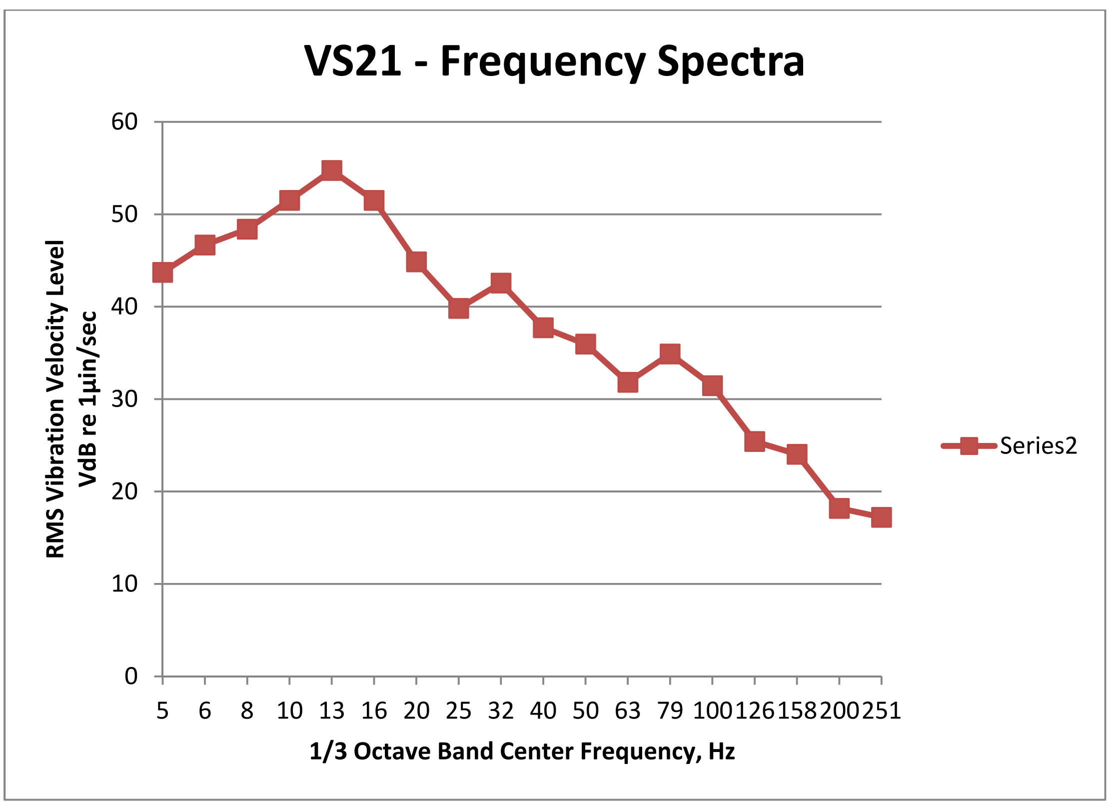

VS16 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
0
10
20
30
40
50
60
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

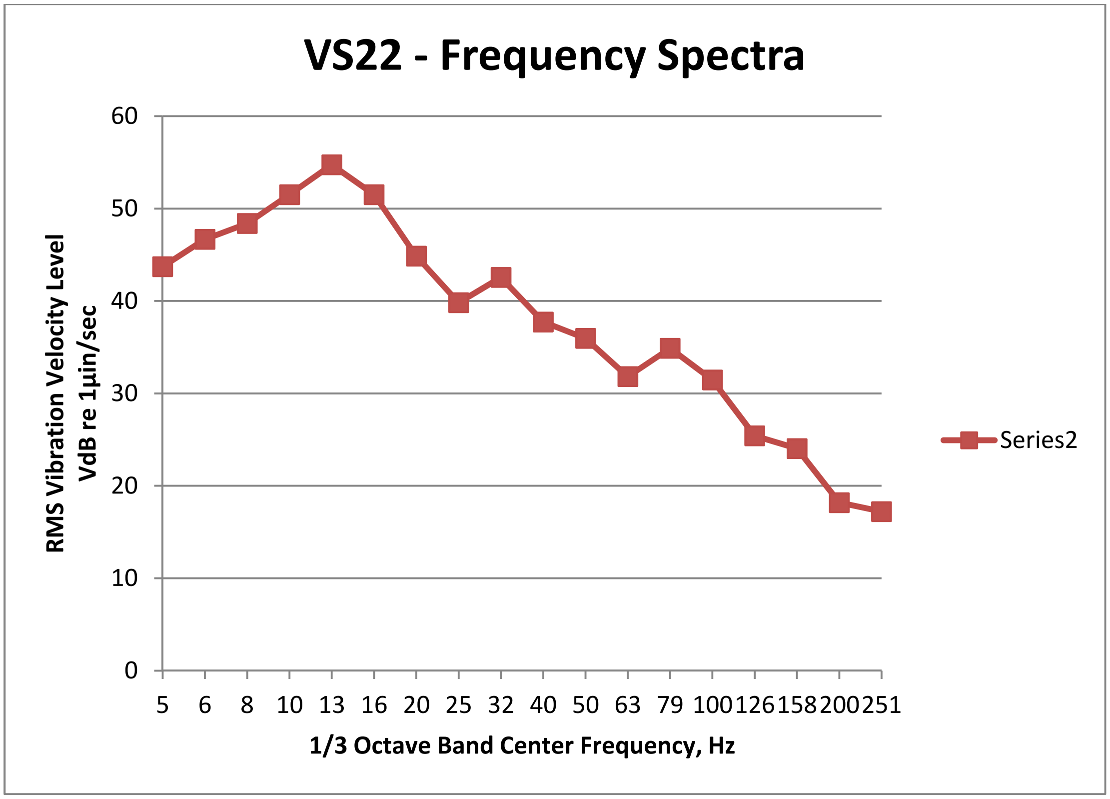

VS17 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
0
10
20
30
40
50
60
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

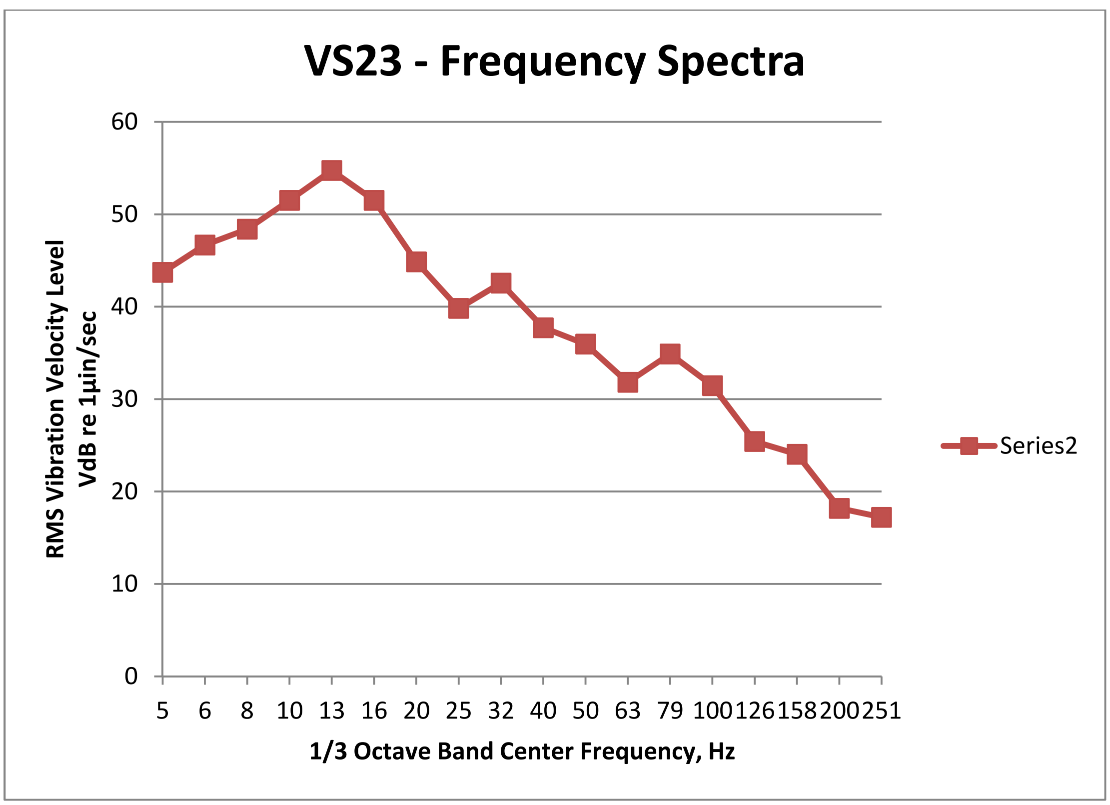

VS18 - Frequency Spectra
60
50
40
30
20
10
0
RMS Vibration Velocity Level
VdB re 1µin/sec
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

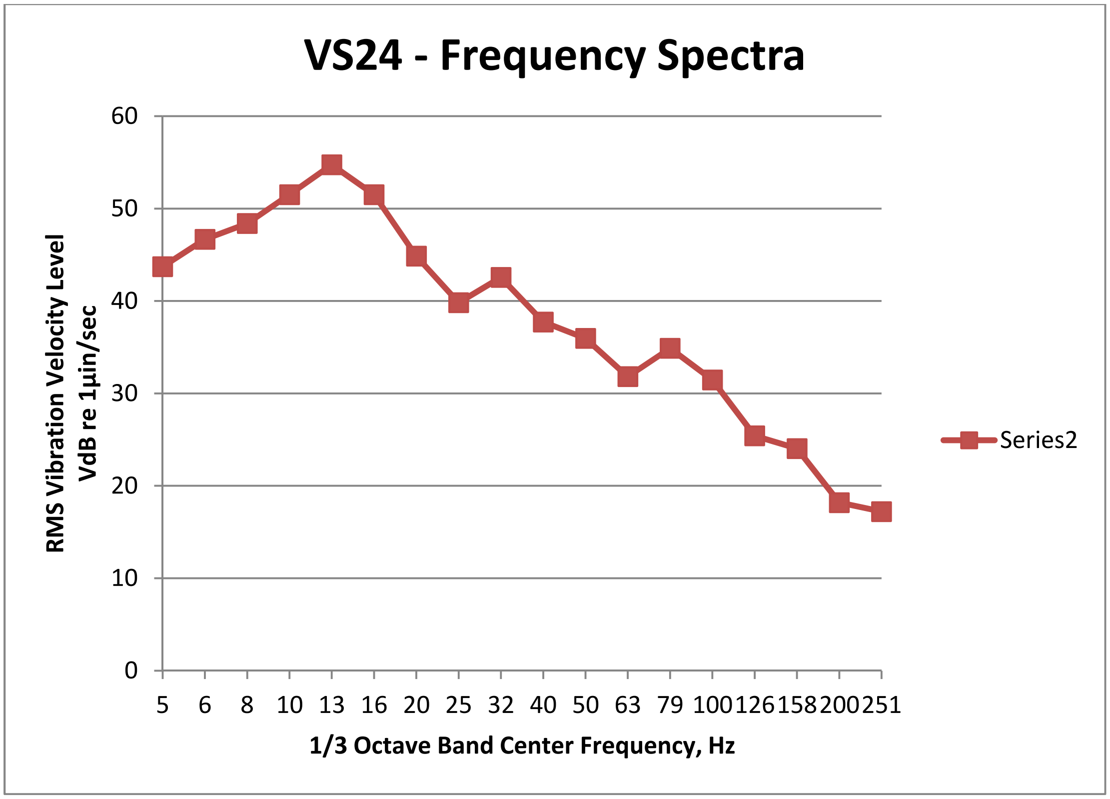

VS19 - Frequency Spectra
60
50
40
30
20
10
0
RMS Vibration Velocity Level
VdB re 1µin/sec
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

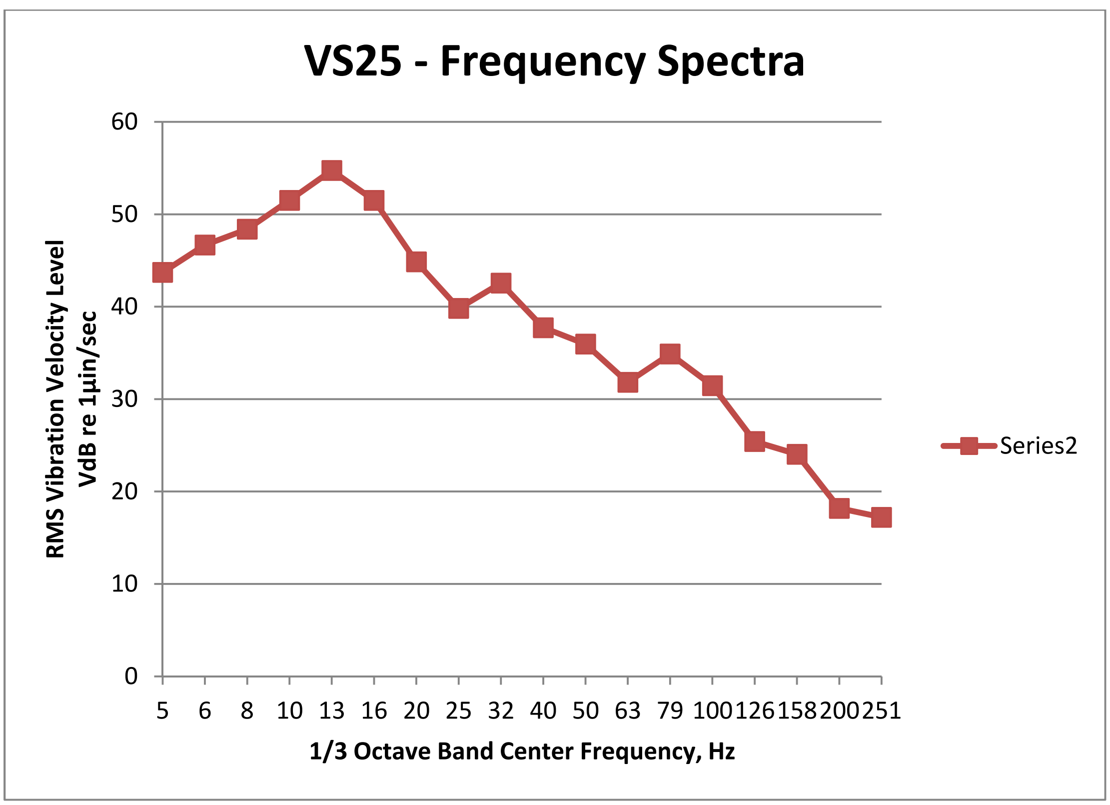

VS20 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

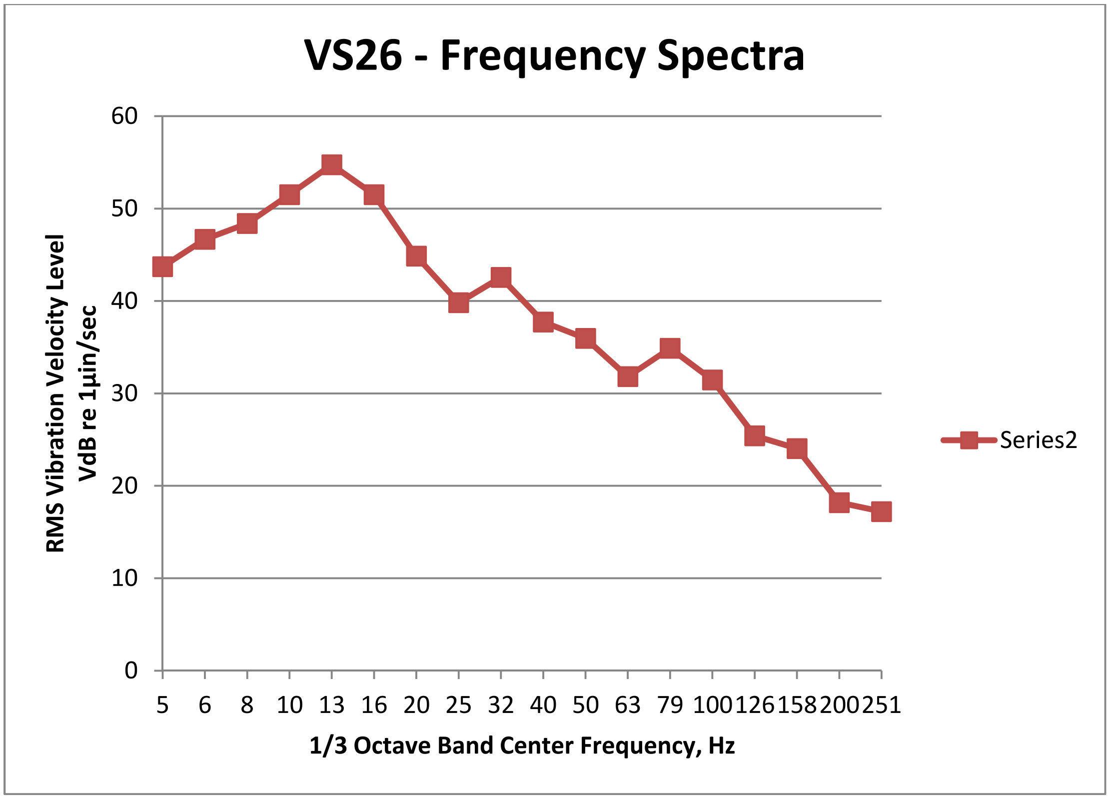

VS21 - Frequency Spectra
RMS Vibration Velocity Level VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2


VS22 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
0
10
20
30
40
50
60
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2


VS23 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
0
10
20
30
40
50
60
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2


VS24 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2


VS25 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2


VS26 - Frequency Spectra
RMS Vibration Velocity Level
VdB re 1µin/sec
60
50
40
30
20
10
0
5 6 8 10 13 16 20 25 32 40 50 63 79 100 126 158 200 251
1/3 Octave Band Center Frequency, Hz
Series2

Appendix E – MTA Purple Line on UM College Park Campus Term Sheet DRAFT for BOR Discussion April 15, 2011

TOPIC: Endorsement of the Proposed Maryland Transit Authority (MTA) Purple Line Light Rail Transit Project

COMMITTEE: Committee of the Whole

DATE OF COMMITTEE MEETING: April 25, 2011

SUMMARY: The Purple Line Light Rail transit project is a 16.3-mile, east-west line planned to operate between New Carrollton and Bethesda. It will link both branches of the Washington Metrorail Red Line at Bethesda and Silver Spring, to the Green Line at College Park, and the Orange Line at New Carrollton.

As presently configured, the proposed Purple Line will traverse the City of College Park and the University of Maryland, College Park, on a surface alignment, from the University's M Square Research Park, to the College Park Metro station, across the University's campus east of Route 1 and the University's main campus west of Route 1, leaving the campus at Campus Drive.

The attached Term Sheet ("TS") is a non-binding framework that was developed to enable MTA and UMCP to proceed to the next phase, "Preliminary Engineering." Also, the non-binding TS will be superseded with an enforceable legally binding MOU/MOA should this project move forward. The TS outlines the scope, schedule, and terms between the MTA and the University for that portion of the rail project ("Project") that is proposed to traverse the campus. The TS covers the planning, design, construction, operation and maintenance of the Project. It addresses pedestrian movement, safety, and security on campus as they relate to the Project. Page 4 describes the actions to be taken, including the provision of an escrow account for the procurement, installation, and maintenance of shielding and/or active cancellation systems for the control of electro-magnetic interference, to minimize interference with campus research facilities. Page 5 includes a section on alignment refinements. The current Locally Preferred Alternative (LPA) alignment designates Campus Drive as the preferred route.

The Term Sheet does not—and is not intended to—resolve every single technical issue. The resolution of many of these issues is properly addressed at the "preliminary engineering" phase together with Federal Transit Administration experts and/or during the development of the legally binding MOU.

ALTERNATIVE(S): The Board could elect to withhold its support of the proposed light rail project.

FISCAL IMPACT: The project, if funded, would be designed, constructed, and maintained by MTA.

CHANCELLOR'S RECOMMENDATION: That the Board of Regents endorse: i) the proposed MTA Purple Line Light Rail transit project; ii) any alignment that maximizes the chances of securing federal funding; and, iii) the Term Sheet between MTA and the University of Maryland, College Park. Further, it is recommended that the University return to the Board for consideration and approval of any resulting MOU/MOA .

COMMITTEE RECOMMENDATION: DATE:

BOARD ACTION: DATE:

SUBMITTED BY: William E. Kirwan (301) 445-1901

Purpose:

The purpose of this Term Sheet is to outline the scope, schedule and terms between the Maryland Transit Administration (MTA) and University of Maryland (UM) for the Purple Line Light Rail Transit segment on the UM Campus (the Project). This term sheet covers the planning, design, construction, operation and maintenance of the Project. ***This Term Sheet is not the final and complete agreement of the parties. The parties will start drafting the final agreements to implement the will of the parties expressed in this Term Sheet***.

Cooperation and Good Faith:

The Parties understand and agree that the success of the Project depends upon timely and open communication and cooperation between the Parties. Each Party agrees to work cooperatively and in good faith toward resolution of any issues. ***The Parties acknowledge that completion of the Project will require negotiation and approval of an acceptable agreement and will require the execution and delivery of a number of future documents, and instruments, the final form and contents of which are not presently determined. The Parties agree to provide the necessary resources and to work in good faith to develop final agreements and to execute and deliver all documents promptly. The Parties acknowledge that the Project is subject to the completion of the federal and state environmental reviews and the preliminary engineering and final design phases, and subject to approval of the Maryland Secretary of Transportation and the University System of Maryland Board of Regents.*** The Parties acknowledge that the project is subject to the requirements of the Federal Transit Administration's (FTA) New Starts Program.

Project Description:

The Purple Line Light Rail transit (LRT) project is a 16.3-mile, east – west LRT line planned to operate between the New Carrollton in Prince George's County and Bethesda in Montgomery County. It will link both branches of the Washington Metrorail Red Line at Bethesda and Silver Spring, to the Green Line at College Park, and the Orange Line at New Carrollton. The project would also connect to all three MARC Train lines, Amtrak, and local bus services. The Purple Line will be Maryland's first east-west fixed guideway transit connector just inside the Beltway. As presently configured, the proposed Purple Line will traverse the City of College Park and the University of Maryland, on a surface alignment, from the University's M Square Research Park, to the College Park Metro station, across the University's campus east of Route 1 and the UM main campus west of Route 1, leaving UM at Campus Drive. The UM East Campus is considered part of the UM Campus for the purposes of this Term Sheet while M Square is not.

The Purple Line will provide a faster, more efficient and more reliable transit option for those traveling east-west in the corridor, as well as those who want to access the existing north-south rail lines. In meeting this goal, the Purple Line will improve connections to the regional Metrorail system and to other rail and bus services. The project will also improve access to jobs by providing better connections between the central business districts (CBD) and major activity centers along the corridor, including Bethesda, Silver Spring, Takoma/Langley Park, University of Maryland/College Park, Riverdale Park, and New Carrollton. The Purple Line will also serve the large populations in the corridor that are heavily dependent on transit, help to support smart growth initiatives and promote community revitalization and transit oriented development where planned.

In 2009, the Maryland Transit Administration (MTA) completed an Alternatives Analysis/Draft Environment Impact Statement (AA/DEIS) for the Project. Subsequently, Maryland Governor, Martin O'Malley identified the Locally Preferred Alternative (LPA) alignment for the project, which traverses through UM campus on a surface alignment. The project description in the LPA includes the basic alignment, proposed station locations, operating plans for the service and some project design options that are to be further evaluated as the project is developed. Presently, the MTA is in the process of further refining the design and developing mitigations to address potential impacts along the route.

Key Terms

General

- The MTA desires to construct the Project as generally described by the July 2009 LPA
- UM desires that the Project goes forward, but that it has minimal impacts to the UM campus.

Partnership Approach

- The underlying assumptions for a future agreement between the parties are as follows:
  - MTA will bear all costs for design, relocation of existing utilities, walks and streets, construction, operations, and maintenance of the Project. UM shall bear the cost of capacity increases or facility improvements.
  - For that portion of the Project that traverses the UM Campus, UM will bear the costs of review and comment on the MTA design plans, its construction plans and schedules, and operations and maintenance plans.
  - The continuity of UM operations during construction is of great importance to UM. MTA will ensure an adequate budget and employ thoughtful logistical planning in cooperation with the UM in order to minimize construction disruption. During construction, the designation of construction staging points and vehicular access will be made in cooperation with and with the prior approval of UM. MTA will pay reasonable costs associated with changes in University operations, for example, moving the UM Shuttle Hub on Campus Drive, that are necessitated by construction or operations.
  - MTA will reimburse reasonable incremental costs incurred by UM for providing any direct or indirect services required to support the construction and future operations and maintenance of the Project within the UM Campus. It is understood that the Project includes all rails, passenger stations, power stations, and overhead catenary supports and other structures built on the UM Campus in association with the Project. The scope of these services and the costs will be detailed in the final agreement, but it is anticipated that they will include police and security services, snow removal and walkway clearing, general grounds keeping and trash removal along the Project alignment and at stations within the UM Campus. The MTA will be responsible for those items directly affecting their operations such as leaf and snow removal on the tracks, and track de-icing.
  - In the event that there is a need to repair utility lines that are located under or immediately adjacent to the Project tracks such that their repair would likely impact the operations of the train, the University will immediately alert MTA. Together MTA and UM will develop an operational plan for repair, although the University reserves the right to make emergency repairs. MTA will be responsible for costs incurred to make repairs beyond those normally borne by the University that are deemed necessary by MTA to keep disturbances of train operations to a minimum, such a tunneling rather than trenching for access to utility lines.
  - **(NOTE: MTA IS SEEKING LEGAL OPINION ON THE FOLLOWING)** MTA will defend and hold the University harmless from claims arising out of MTA's design, construction, maintenance and operation of the Project. It is recognized that the University and the MTA are entitled to the immunities of the State of Maryland. MTA shall reimburse UM for any increase in its State Insurance Trust Fund premiums attributable to MTA's construction,

maintenance or operation of the Project.

- Once the Project is operational, it is anticipated that the UM Shuttle routes between the Campus and the College Park Metro Station and M Square and Silver Spring will be discontinued. The MTA and UM will explore the feasibility of an agreement wherein that the operating costs saved by discontinuing these routes would be transferred to MTA as full or partial payment to allow all members of our community to use the entire Purple Line at no or reduced cost.
- UM will make available easements and property needed for the Project and supporting facilities on the Campus at no cost to the MTA.
- The obligations of the MTA under this Term Sheet and as incorporated in the final agreement or agreements between the UM and the MTA shall be made binding upon any future third party successor, owner, or operator of the Project.

Pedestrian Movement on Campus

- Both MTA and UM agree that the safety of the students, faculty, staff, and visitors to UM and the safety of the MTA staff, operators, and riders are the primary responsibility in the planning, design construction, maintenance, and operation of the Project.
  - Pedestrian right of way on campus will be maintained.
  - MTA agrees to limit the maximum speed of operations on the Project 15 mph as an Electro-Magnetic Interference mitigation measure (EMI).
  - Due corridor-wide constraints, the trains will be limited to trains not to exceed a total length of 200'.
- MTA agrees and accepts that within the UM Campus pedestrian traffic will have the right of way over the Project. The implementation of this requirement may result in the following;
  - Operators of vehicles the Project will be instructed to always yield to pedestrians, just as the existing UM transit buses.
  - All cross-walks currently designated and any that the University in the future believes are necessary to add for pedestrian mobility will be recognized by the MTA. Crosswalks will not be consolidated unless agreed to by the University.
  - No additional barriers to pedestrian movement across the Project alignment through the center of Campus, and specifically on Union Drive/Campus Drive, will be required by MTA. Barriers along the alignment in other open areas will be considered on a case by case basis and agreed to by both parties.
  - UM will work with MTA to determine non-pedestrian areas within the UM Campus where higher speeds can be established. MTA acknowledges and accepts that the normal function and operations of UM Campus, as well as during football and other special events, may affect MTA schedules and operations. UM and MTA will work cooperatively to minimize disruption of Project service.

Safety and Security

- MTA and UM both have security forces with broad police powers. To enhance the safety and security of the Project operations within the UM Campus, UM and MTA will develop an integrated communications system or protocol to ensure the timely exchange of information and coordination of MTA's and UM's responses to any events on the Project or Campus that could affect the other party's operations or safety.
- Incidents involving students, faculty, staff, and UM visitors will be handled jointly.

Minimizing Interference with UM Research Facilities

- MTA will provide an escrow account for the procurement, installation, and maintenance of shielding and/or active cancellation systems for the control of Electro-Magnetic Interference (EMI) where the EMI effects from the project exceed the greater of the ambient or 0.1mG at existing and potential research laboratories for a period of 30 years, after which UM and its research partners will design their research activities to accommodate the background conditions resulting from the Project. The exact amount for the escrow account will be determined in the final agreement, but a working value of $40,000 per laboratory in the building areas identified by the MTA model as likely to experience EMI in excess of the ambient or 0.1mG from train operations.
- MTA will design the guideway adjacent to vibration sensitive facilities to minimize ground-borne vibration consistent with proven industry practices and maintenance requirements to meet the greater of the ambient vibration levels or the National Institute of Standards and Testing (NIST) level A within 100 feet of the nearest track centerline at existing and potential research laboratories for a period of 30 years, after which UM and its research partners will design their research activities to accommodate the background conditions resulting from the Project. The MTA will provide an escrow account for the maintenance of installed mitigation measures. The exact amount for the escrow account will be determined in the final agreement after MTA completes an impact and mitigation analysis.
- MTA will design the guideway and electric traction power system to control stray current generated by the Project. Isolation, collection, and active suppression systems may be employed. The funding, operation, maintenance, repair, and replacement of these systems will be the sole responsibility of MTA.
- MTA agrees to provide a combination of source mitigation, vehicle-borne mitigation (such as skirts and cowls), receptor mitigation, and/or maintenance practices to control noise generated by the Project.
- All power for the operations of the Project is to be supplied by MTA.
- MTA agrees to specific design, operations, and maintenance criteria to monitor and control EMI , stray current, vibration and noise on the Project including:
    - Establishment of a monitoring program to verify the efficacy of the design and operational criteria in meeting the limits detailed in the various studies and documents prepared by the MTA and UM and as detailed in the final agreement for EMI, stray current, noise, and vibration. MTA shall be responsible for the costs of the monitoring program, and will perform the monitoring in conjunction with UM.
    - Establish a protocol to address correction of system failure(s) that lead to excessive EMI or vibration at the research facilities. The protocols will include repair, modification, and maintenance to isolation, shielding, collection, and/or active control systems in addition to operational changes. The costs of implementing the protocols shall be the responsibility of MTA.
    - In order to limit EMI to the extent possible in the areas of current or future research facilities/activities, the traction power system will employ a split wire high-low power supply or comparable technologies to meet established criteria, and Project train speeds will not exceed 15 mph in these areas.
    - MTA agrees to limit trains operating through the Campus to a maximum length of 200 feet to control EMI along the Campus segments with sensitive research equipment and activities.

Alignment Refinements

- The MTA acknowledges that Campus Drive can remain available to traffic, if that alignment is chosen.
- The MTA acknowledges the iconic significance of the M circle and will seek to maintain its character.
- Should a grade separated or alternate alignment be considered or constructed for the Project, the MTA and UM commit to exploring more economical design and construction techniques and further agree not to presume such options are precluded in deference to perceived aesthetic or landscape impacts that may result from such techniques.
- In the event that a grade separated alignment is selected, UM agrees to place cameras at the entrance and exit portals and monitor them at all times. UM agrees that other systems may be employed by MTA to monitor intrusions at the tunnels and that MTA will notify UM Department of Public Safety (DPS) of an intrusion.
  - The DPS and MTA emergency operations center will coordinate to modify train operations until the trespassers are removed and the tunnel is cleared by security forces.
  - UM DPS will respond immediately to remove any person entering the tunnel or portal area.

Future Growth of the UM Campus

- 2011 and Future Master Plan Updates. UM encourages the MTA to present to and participate in the UM Master Plan Committees, attend all public meetings, and provide comments to the Master Planning Steering Committee.
- MTA and UM will work together to minimize the impact on UM's ability to development land in M Square by construction of the tracks and station location. This includes loss of developable space and associated parking.
- The Master Plan will show and accommodate a fully integrated Project through the Campus.
- The MTA will seek to minimize the taking of parking spaces on Campus and will work with UM to replace lost spaces.
- The MTA and UM recognize the importance of the Project respecting the Campus aesthetic context and will work collaboratively to develop the various design features of the Project within the Campus.

University System of Maryland Board of Regents
University of Maryland, Baltimore
April 25, 2011

Minutes of the Public Session

1. Call to Order. Chairman Kendall called the special meeting of the University System of Maryland Board of Regents to order at 10:16 a.m. on Monday, April 25, 2011 at the University of Maryland, Baltimore. Those in attendance or participating by conference call were: Chairman Kendall; Regents Attman, Augustine, Florestano, Gonzales, Gooden, Gossett, Hance, Johnson, Kelly, McMillen, Reid, Slater, and Young; Chancellor Kirwan, Vice Chancellors Goldstein, Raley, and Vivona; Associate Vice Chancellors Hogan and Moultrie; Assistant Attorney General Travieso and Short; Ms. Doyle, Ms. Ryan, USM Staff.

2. Reconvene to Executive Session. (Moved by Chairman Kendall; seconded by Regent Gossett, unanimously approved)

3. Convene in Public Session. At the conclusion of the executive session, Chairman Kendall convened the BOR in public session at 10:38 a.m.

4. Committee of the Whole.
    a. Endorsement of the Proposed Maryland Transit Authority (MTA) Purple Line Light Rail Transit Project (Moved by Regent Florestano; seconded by Regent Slater, unanimously approved)
    b. Biennial Nonexempt Market Salary Survey Report — Nonexempt Staff Employees Salary Structure (Moved by Regent Kelly, seconded by Regent Reid, unanimously approved)
    c. Resolution for William Donald Schaefer (Moved by Regent Attman, seconded by Regent Young, unanimously approved)

The meeting adjourned at 11:16 a.m.

Appendix F – Purple Line Project, University of Maryland Ambient Vibration Study, August 13, 2009

Purple Line Project

University of Maryland

Ambient Vibration Study

13 August 2009

Prepared For:
Maryland Department of Transportation

Prepared By:
Parsons Brinckerhoff Corporation
75 Arlington Street
Boston, MA 02116

Assisted By:
Phoenix Noise & Vibration, LLC
930 North East Street, Suite 4
Frederick, MD 21701

Executive Summary

An ambient vibration study was conducted on the campus of the University of Maryland (UM) in support of the Purple Line Project. The study was performed in April 2009 and included vibration measurements inside and outside of 16 buildings and two parking lots, as well as measurements near 30 vibration-sensitive laboratory devices. The measurements were performed for two reasons; (1) to retest and validate the ambient vibration levels reported by Vibro-Acoustics in their report dated 10/14/08, and (2) to determine ambient vibration conditions under which various vibration-sensitive devices are currently operating in an acceptable manner.

In contrast to the Vibro-Acoustics study, vibration measurements in this case were performed specifically to include the effects of typical student activity and shuttle bus movement while the semester was still in session. All the measurements in this study were performed over 15 minute intervals to insure that multiple shuttle bus passby events would be included in the vibration data. Also, measurements were performed not only in the basements of 16 identified buildings but also on the exterior grounds immediately adjacent to the buildings. In this manner the behavior of the buildings themselves can be determined relative to the ground vibrations outside the buildings. Also in contrast to the prior study, measurements in this study were performed in close proximity to 30 vibration-sensitive laboratory devices in various buildings identified by UM researches and facility managers.

In summary, the ambient vibration levels measured in third-octave band format from 1 Hz to 100 Hz inside the basements of 16 buildings proved to be remarkably similar to the levels reported previously by Vibro-Acoustics. However, the comparison of exterior and interior vibration levels and the levels measured in close proximity to the sensitive devices revealed some interesting findings.

- When averaged over all 16 buildings, the RMS vibration velocity levels inside the buildings' basements averaged between 7 and 58 micro-inches/second, with the minimum occurring in the 2.5 Hz third-octave band and the maximum occurring in the 10 Hz third-octave band. Levels measured by Vibro-Acoustics averaged from about 5 to 97 micro-inches/second with the same general distribution over the lower third-octave bands but with higher levels reported in the upper bands, particularly in the 31.5 Hz band.

- When comparing average building vibration levels to exterior grounds, the buildings tended to vibrate less than the ground in the third-octave frequency bands below 5 Hz. This pattern would be expected given the coupling/transmissibility inefficiencies between the ground and the buildings. The buildings and the outside grounds tended to vibrate coincidently (i.e. the same) within the 5 Hz to 63 Hz bands. But at the higher frequency bands of 63 Hz to 100 Hz the buildings actually vibrated more than the outside grounds, indicating that vibration sources within the buildings themselves were dominating.

- At UM's vibration-sensitive devices, the vibration velocity levels in the vertical (Z) direction were notably higher than in either the latitudinal (X) or longitudinal (Y) directions. The majority of the vibration levels throughout the 1 Hz to 100 Hz band region tended to range between 10 and 100 micro-inches/second, with several results elevating by an order of magnitude into the 100 to 1,000 micro-inches/second range in the mid-frequency bands.

Terminology

Vibration levels may be quantified using several different metrics depending on what issue is being evaluated. Vibration is mechanical energy in oscillatory motion and can therefore be evaluated in terms of its instantaneous (Peak) or average (root-mean-square, RMS) acceleration, velocity or displacement. For structures and sensitive devices it is most common to evaluate the vibration *velocity* component, which is commonly expressed in units of inches/second.

The broadband peak particle velocity (PPV) is the preferred metric for evaluating potential damage to buildings and structures from impulsive sources. PPV amplitudes are expressed in engineering units of inches/second. Sensitive devices, however, require a more in-depth evaluation than do structures, particularly for low level, low frequency vibrational energy within the range of approximately 1 Hz to 100 Hz. RMS levels are the preferred metric for evaluating sensitive devices because it allows for time-averaging of the spectral vibration levels. When evaluated in narrowband or third-octave band format, the resulting velocity levels are usually expressed in engineering units of *micro*-inches/second.

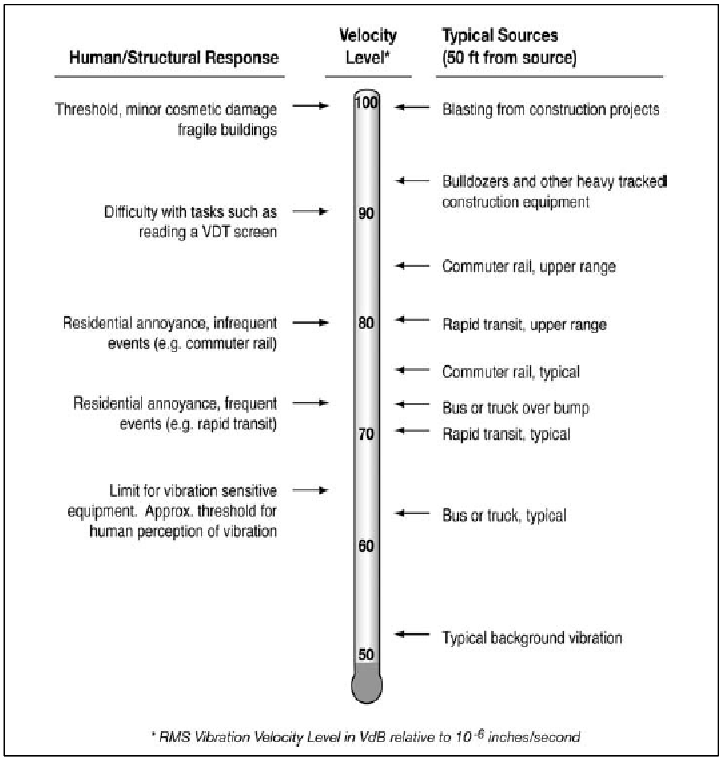


Figure 1. Typical Vibration Sources and Levels

As shown in **Figure 1**, vibration velocity levels can also be expressed in decibel units (VdB) where the engineering unit is logarithmically compared to a reference velocity level of 1 micro-inch/second. Decibel format can be useful, especially when describing a large dynamic range or relative changes in vibration levels.

Where the PPV represents the highest instantaneous peak vibration level, the RMS vibration level represents a time and energy-averaged vibration level. Therefore, potential damages to structures are usually evaluated in terms of PPV levels, where human perception, annoyance, and vibration interference with sensitive devices are usually evaluated in terms of RMS vibration velocity.

Data Collection Methodology

Vibration measurements were conducted on the campus of the University of Maryland during three typical mid-week days from Tuesday 4/28/09 through Thursday 4/30/09. Measurements were performed from about 9 AM to 5 PM each day using three teams of engineers/data collection systems in order to measure levels at 16 buildings, two parking lots, and in close proximity to 30 sensitive laboratory devices. The locations of the buildings, and the proposed route for the Purple Line, can be seen on the campus map reproduced in **Figure 2**.

In general, the vibration measurement systems were comprised of very sensitive (i.e. 10 V/g) accelerometers with appropriate power supplies to provide ICP power for the accelerometers' internal pre-amplifiers. For measurements performed indoors the accelerometers were stud-mounted to large steel seismic blocks weighing between 30 to 40 lbs, as shown in **Photo 1**. The blocks were placed on the floor on a thin 1/8-inch thick shredded-tire rubber mat to act as a vibration low-pass filter in order to avoid exciting the accelerometers' resonance frequencies. For the exterior grounds measurements, as shown in **Photo 2**, a 15-inch long (3/4-inch diameter) steel spike was driven into the ground and the accelerometer was stud-mounted on top of the stake. Both of these mounting methods are standard industry practices and are recommended by agencies such as the Federal Transit Administration.

Photo 1. Vibration measurements in basement

Photo 2. Vibration measurements in ground

The same type of steel mounting block method was used to perform tri-axial vibration measurements near 30 of UM's vibration-sensitive devices. As shown in **Photo 3**, three accelerometers were stud mounted in three mutually-orthogonal directions (X, Y, Z) on the block and placed on the floor near the sensitive devices. The three vibration signals generated by the accelerometers were simultaneously recorded on multi-channel solid state data recorders (seen on near table).

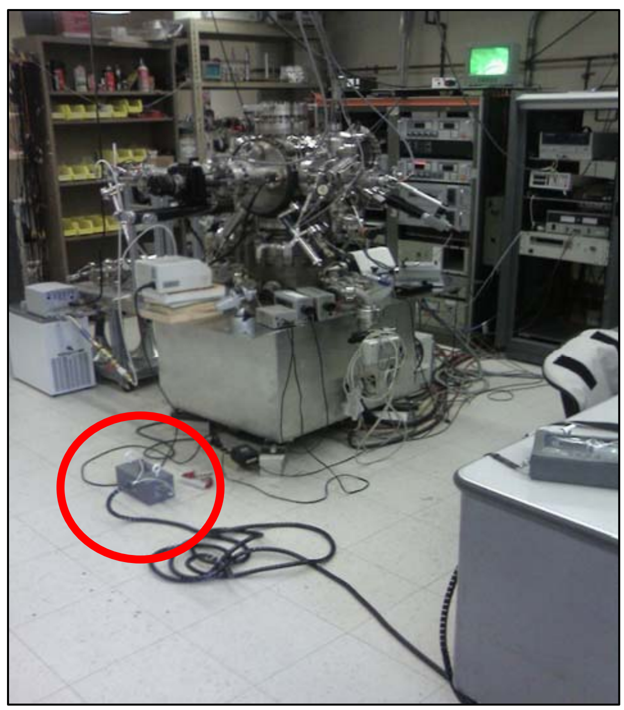


Photo 3. Tri-axial vibration measurements near UM's sensitive devices

The vibration acceleration signals generated by the accelerometers during the 15 minute samples were streamed into solid-state digital recorders in order to store the data as real-time audio files (i.e. wav files). This allowed for the data to be subsequently replayed, analyzed and reduced back in the office using third-octave band analyzers and Excel spreadsheets. The spreadsheets allowed for numerical integration from acceleration to velocity as well as presentation and comparison of results. The vibration velocity data was reduced in third-octave bands ranging from 1 Hz to 100 Hz in engineering units of micro-inches/second.

Vibration measurements were performed inside the basements or on the first floors (for buildings without basements) by positioning the mounting block and accelerometer in a vertical direction as close as possible to the façade of the building facing the proposed Purple Line route. Similarly, the measurements on the grounds outside the buildings were also performed as close to the same façade of the buildings as possible. Typically this meant a distance of just a few feet from the buildings' facades. Care was taken to avoid extraneous vibration-producing sources such as pedestrians, compressors, fans and other rotating machinery.

As mentioned above, vibration data was collected for 15 minute intervals at each measurement point in order to insure that several shuttle bus passby events were included in the data. Observers were used to count shuttle bus traffic activity, as well as the number of medium trucks (MT) and heavy trucks (HT), during each measurement session. Medium trucks were defined as vehicles with two axles and six wheels, and heavy trucks were defined as vehicles having three or more axles. **Table 1** summarizes the 16 buildings and two parking lots, and the number of vehicle passby events, for each of the basement/grounds vertical vibration measurements.

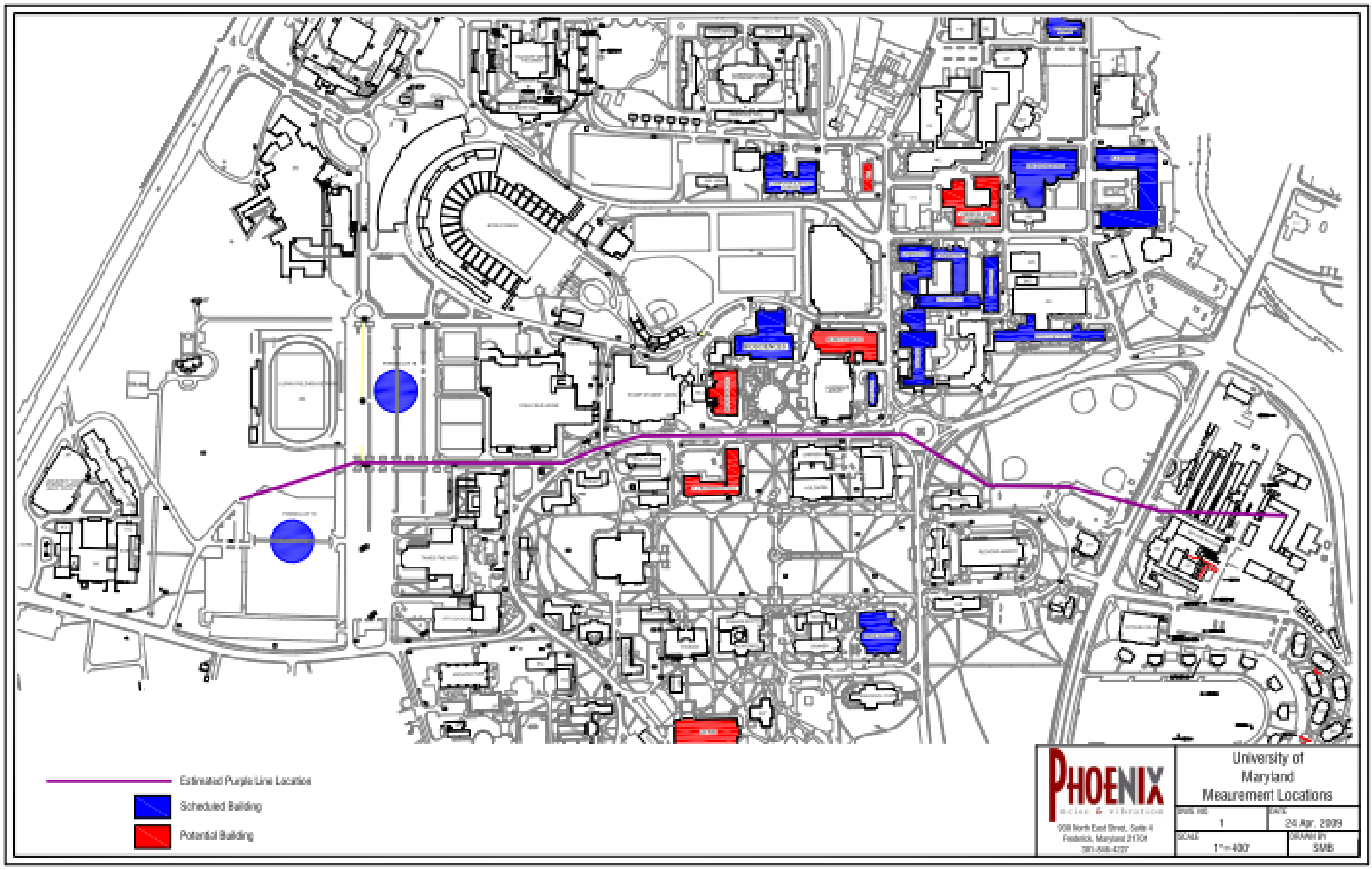


Figure 2. Buildings/Locations of Ambient Vibration Measurements

Table 1. Vibration Measurements at Buildings/Grounds

Building Abbrev. – No.	Building Name	Location	Vehicle Passbys
EGL – 089	Martin Engineering Building	Basement Room 0128	Bus = 15, MT = 8, HT = 0
EGL – 089	Martin Engineering Building	Outside Grounds	Bus = 14, MT = 0, HT = 0
PHY – 082	Physics Building	Basement Room 0113	Bus = 13, MT = 3, HT = 0
PHY – 082	Physics Building	Outside Grounds	Bus = 11, MT = 3, HT = 2
CHM – 091	Chemistry Building	Basement Room B0129C	Bus = 15, MT = 1, HT = 0
CHM – 091	Chemistry Building	Outside Grounds	Bus = 11, MT = 4, HT = 1
AVW – 115	AV Williams Building	1st Floor Room 1241	Bus = 10, MT = 1, HT = 1
AVW – 115	AV Williams Building	Outside Grounds	Bus = 19, MT = 4, HT = 2
KEB – 225	Kim Engineering Building	1st Floor Lobby	Bus = 12, MT = 5, HT = 0
KEB – 225	Kim Engineering Building	Outside Grounds	Bus = 23, MT = 7, HT = 2
CHE – 090	Chemistry/Nuclear Eng. Building	Basement Room 1111	Bus = 21, MT = 2, HT = 5
CHE – 090	Chemistry/Nuclear Eng. Building	Outside Grounds	Bus = 22, MT = 4, HT = 3
BMS – 413	Bimolecular Sciences Building	1st Floor Room 1120	*Bus = 1, MT = 0, HT = 0
BMS – 413	Bimolecular Sciences Building	Outside Grounds	*Bus = 1, MT = 0, HT = 0
IPT – 085	Institute for Physics Technology	Basement Room B0112	Bus = 14, MT = 3, HT = 0
IPT – 085	Institute for Physics Technology	Outside Grounds	Bus = 8, MT = 7, HT = 0
CSS – 224	Computer Space Science Building	Basement Room B0213	Bus = 4, MT = 6, HT = 1
CSS – 224	Computer Space Science Building	Outside Grounds	Bus = 2, MT = 9, HT = 1
BPS – 144	Bioscience Research Building	1st Floor Bathroom	Bus = 11, MT = 1, HT = 1
BPS – 144	Bioscience Research Building	Outside Grounds	Bus = 17, MT = 8, HT = 0
MCB – 231	Microbiology Building	Basement Room 0107G	Bus = 14, MT = 1, HT = 0
MCB – 231	Microbiology Building	Outside Grounds	Bus = 14, MT = 3, HT = 2
HJP – 073	HJ Patterson Building	Basement Room 0109	Bus = 13, MT = 3, HT = 1
HJP – 073	HJ Patterson Building	Outside Grounds	Bus = 14, MT = 2, HT = 1
GEO – 237	Geology Building	1st Floor Room 1101	Bus = 17, MT = 4, HT = 1
GEO – 237	Geology Building	Outside Grounds	Bus = 15, MT = 6, HT = 0
PLS – 036	Plant Science Building	Basement Room 0114	Bus = 16, MT = 6, HT = 0
PLS – 036	Plant Science Building	Outside Grounds	Bus = 20, MT = 6, HT = 0
MMH – 046	Marie Mount Hall Building	Basement Room 1314	*Bus = 0, MT = 9, HT = 0
MMH – 046	Marie Mount Hall Building	Outside Grounds	*Bus = 0, MT = 4, HT = 0
LEF – 038	LeFrak Hall Building	1st Floor Room 0101	*Bus = 0, MT = 0, HT = 0
LEF – 038	LeFrak Hall Building	Outside Grounds	*Bus = 0, MT = 0, HT = 0
Parking Lot 1D	Parking Lot 1D	Ground near center of lot	Bus = 6, MT = 4, HT = 0
Parking Lot 1B	Parking Lot 1B	Ground near center of lot	Bus = 0, MT = 5, HT = 0

(*) indicates buildings which were too far away from any roadway to be influenced by shuttle buses

Vibration Instrumentation

An extensive array of vibration instrumentation was used to conduct the ambient vibration measurements in this study. There were three vibration measurement systems used in this case. One system was used by engineering staff from Parsons Brinckerhoff to perform measurements inside the basements and exterior grounds for 16 campus buildings and two parking lots, while two teams of engineering staff from Phoenix Noise & Vibration performed the measurements in close proximity to 30 vibration-sensitive devices in various laboratories. The basement and exterior ground measurements were performed in the vertical (Z) direction, while the measurements performed in close proximity to UM's sensitive devices were performed in three mutually-orthogonal directions; latitudinal (X), longitudinal (Y) and vertical (Z).

The makes, models and use purposes of the vibration instrumentation used in this study are summarized in **Table 2**. The three measurement systems were calibrated in the field using a mini-shaker which produced 1 m/s^2 RMS at 160 Hz, and all of the instrumentation had currently valid calibration compliance certificates from either the equipment's manufacturer or an independent testing laboratory.

Table 2. Vibration Measurement Instrumentation

Make	Model	Item	Use Purpose	Serial No.
Wilcoxon	731-207	Accelerometer (10 V/g)	Basements & Grounds	2174
Norsonics	NOR-140	Vibration Analyzer and Data Recorder	Basements & Grounds	1402888
Pioneer Hill	SpectraPLUS	PC-based Vibration Analyzer	Basements & Grounds	5763
RION	DA-20	4ch Data Recorder	Sensitive Devices 1	10870900
PCB	393B05	Accelerometer (10 V/g)	Sensitive Devices 1-X	20899
PCB	393B05	Accelerometer (10 V/g)	Sensitive Devices 1-Y	22852
PCB	393B05	Accelerometer (10 V/g)	Sensitive Devices 1-Z	23569
RION	DA-20	4ch Data Recorder	Sensitive Devices 2	00260262
PCB	393B05	Accelerometer (10 V/g)	Sensitive Devices 2-X	25409
PCB	393B05	Accelerometer (10 V/g)	Sensitive Devices 2-Y	24706
PCB	393B05	Accelerometer (10 V/g)	Sensitive Devices 2-Z	25408
MMF	VC100	Vibration Shaker (1 m/s^2 rms at 160 Hz)	Calibrate all equipment	003243

Vibration Criteria

While there are no specific vibration criteria limits applicable to this project, there are several approaches that can be considered for their relevancy in this case to protect UM's vibration-sensitive devices from being adversely affected by Purple Line vibrations. The criteria options presented here are for discussion and consideration only. The most appropriate criteria will have to be determined prior to the next phase of the project which will involve predictive modeling and evaluation of future project-generated vibration levels.

<u>Existing Conditions Criterion</u>

One obvious approach would be that the ambient vibration velocity levels measured through this study could serve as vibration criterion which should not be exceeded in the future. UM's vibration-sensitive devices are operating successfully under current conditions, therefore they should continue to function properly in the future providing the Purple Line's vibrations do not significantly exceed current ambient levels.

<u>Manufacturer Specifications</u>

The manufacturer of each of UM's sensitive devices should be able to provide vibration specifications indicating maximum allowable vibration levels for proper function. This may be an arduous and time consuming approach because there are at least 30 different sensitive devices to research, but it would allow for evaluating and controlling Purple Line vibration emissions to their maximum allowable levels.

Vibration Criteria (VC) Curves

There is a family of vibration criteria curves, shown here in **Figure 3**, intended to protect sensitive devices from excessive vibration. These criteria originated with the Institute of Environmental Sciences and Technology (IEST) and were published in their Standards RP-CC012.2 and RP-CC024. The FTA subsequently adopted and recommended these criteria as well in their *Transit Noise and Vibration Impact Assessment Manual* (May 2006). The FTA Manual only shows VC curves down to VC-E (i.e. 125 micro-inch/second, or 42 VdB), however the curves can be extended lower to VC-F and VC-G as well. In general, each lower VC curve represents half the vibration velocity level of the one above it.

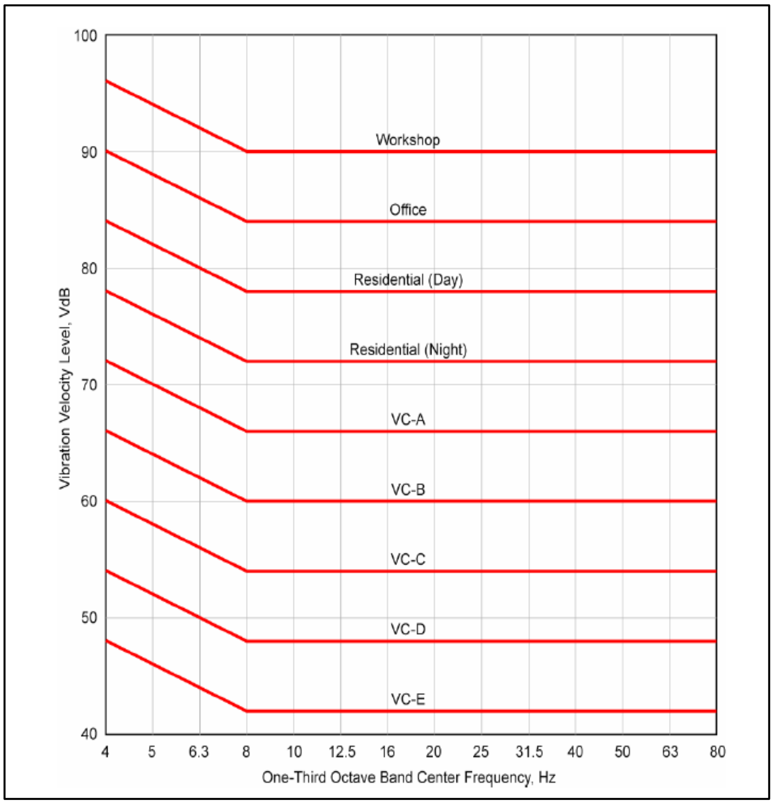


Figure 3. Vibration Criteria (VC) Curves for Sensitive Devices

The VC curves elbow upwards at and below the 8 Hz third-octave band, however they should be extended linearly (flat) for particularly sensitive devices whose mounting systems are not fully understood. **Table 3** provides the vibration velocity levels for each VC curve expressed in engineering units and decibels, and a description for the intended use of each criterion curve.

Table 3. VC Vibration Criteria Limits and Intended Use

VC Curve Name	Vibration Limit		Intended Use
	Micro-inch/second	VdB re 1 u-ips	
VC-A	2,000	66	Adequate for medium- to high-power optical microscopes (400X), microbalances, optical balances, and similar specialized equipment.
VC-B	1,000	60	Adequate for high-power optical microscopes (1000X), inspection and lithography equipment to 3 micron line widths.
VC-C	500	54	Appropriate for most lithography and inspection equipment to 1 micron detail size.
VC-D	250	48	Suitable in most instances for the most demanding equipment, including electron microscopes operating to the limits of their capability.
VC-E	125	42	The most demanding criterion for extremely sensitive equipment.
VC-F	63	36	Not described.
VC-G	31	30	Not described.

Discussion and Results

The results of the ambient vibration study can be separated into three categories, namely:

(1) ambient vibration velocity levels found in the basements and outside grounds of the 16 buildings and two parking lots
(2) the relative relationship, or coupling transmissibility, between the buildings and the outside grounds - which will be useful for future predictive modeling
(3) ambient vibration levels currently affecting UM's vibration-sensitive devices

<u>(1) Ambient Building Vibration Levels</u>

Figure 4 shows the average RMS vertical vibration velocity levels, both inside the basements and outside on the grounds, of the 16 buildings listed in **Table 1**. The results are expressed in engineering units of micro-inches/second, and are superimposed over the VC criteria curves simply for reference at this point. Also shown, for comparative purposes only, are the results published in Vibro-Acoustics' ambient vibration report dated 10/14/08.

When averaged over all 16 buildings, the RMS vibration velocity levels inside the buildings' basements averaged between 7 and 58 micro-inches/second, with the minimum occurring in the 2.5 Hz third-octave band and the maximum occurring in the 10 Hz third-octave band. Levels measured by Vibro-Acoustics averaged from about 5 to 97 micro-inches/second with the same general distribution over the lower third-octave bands but with higher levels reported in the upper bands, particularly in the 31.5 Hz band.

The higher levels that Vibro-Acoustics measured, most notably in the telltale 31.5 Hz and 63 Hz bands, could be due to their accelerometer being placed closer to rotating machinery or electrical sources inside the buildings, or being placed closer to the center of rooms where floor surfaces are more flexible than near the external façade walls. The differences may also be explained by the measurement sample durations where Vibro-Acoustics' relatively short 15-second samples may have been influenced by transient events whereas this study's 15-minute samples allowed for significant data spectral averaging and signal stabilization.

The ambient vertical vibration level results for each of the 16 individual buildings are shown in **Figures 5 and 6** for interior basement locations and exterior grounds locations, respectively.

Of the 16 buildings, interior vibration levels were highest inside the AVW Building, secondly inside the GEO Building, and thirdly inside the CHM Building. The reasons for, or sources contributing to, the vibration results measured inside the buildings were not specifically identified as part of this study. The dashed line shown in **Figure 5** represents the average interior vibration level for all 16 buildings combined. This average interior vibration level is also shown in **Figure 4.**

For the exterior grounds of the 16 buildings, the highest vibration levels were found outside the HJP Building, secondly outside the AVW Building, and thirdly outside the IPT Building. Again, the reasons for, or sources contributing to, the vibration results measured outside the buildings were not specifically identified as part of this study. The dashed line shown in **Figure 6** represents the average exterior vibration level for all 16 buildings combined. This average exterior vibration level is also shown in **Figure 4.**

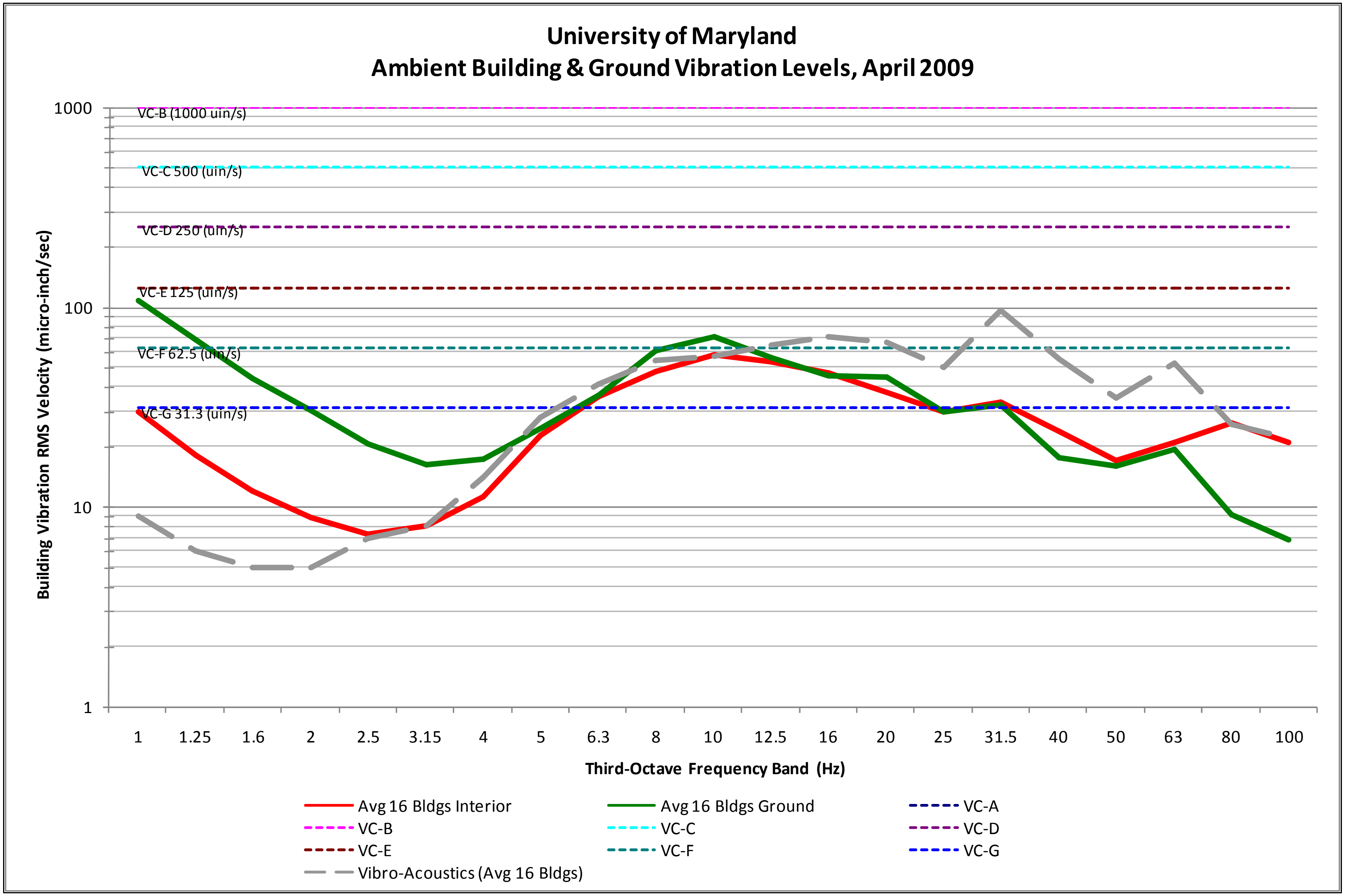


Figure 4. Average Ambient Vertical Vibration Velocity Levels

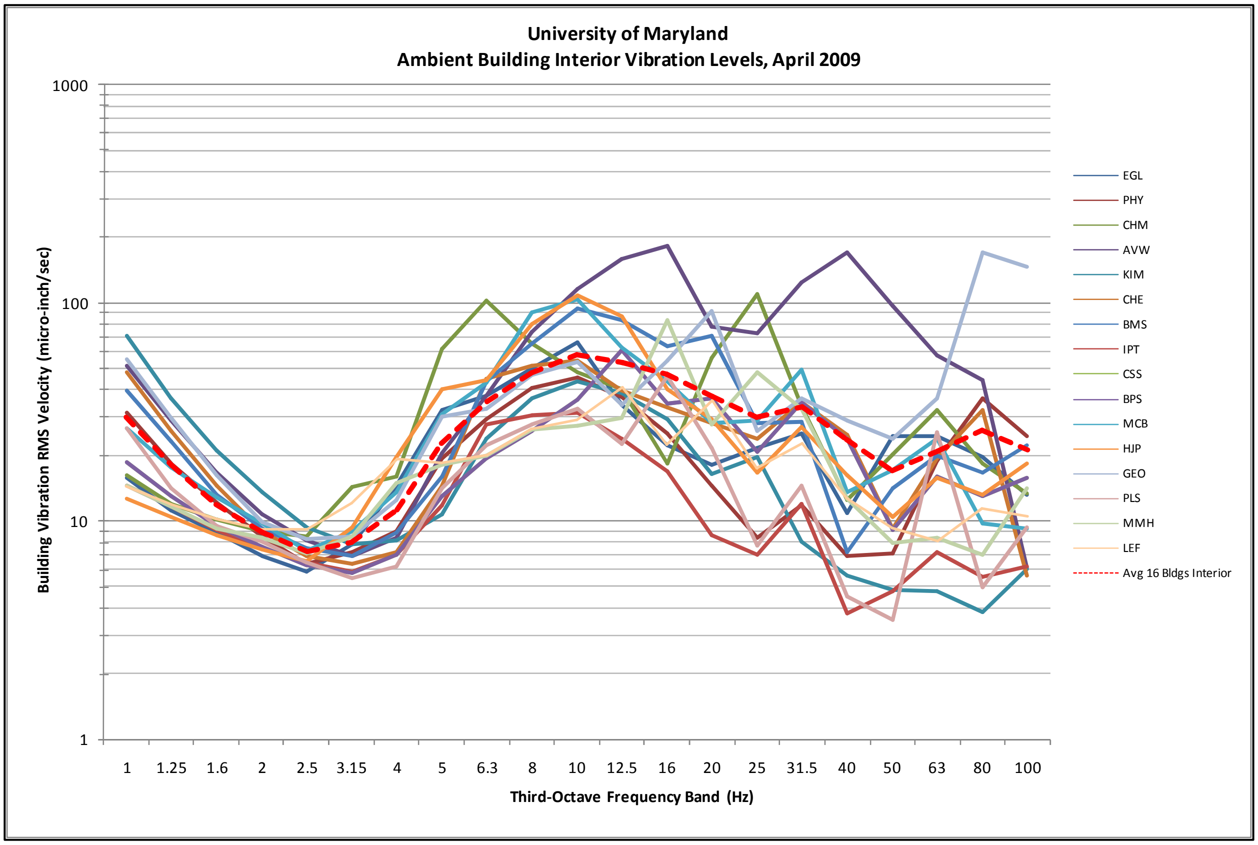


Figure 5. Ambient Vertical Vibration Velocity Levels Inside UM's 16 Buildings

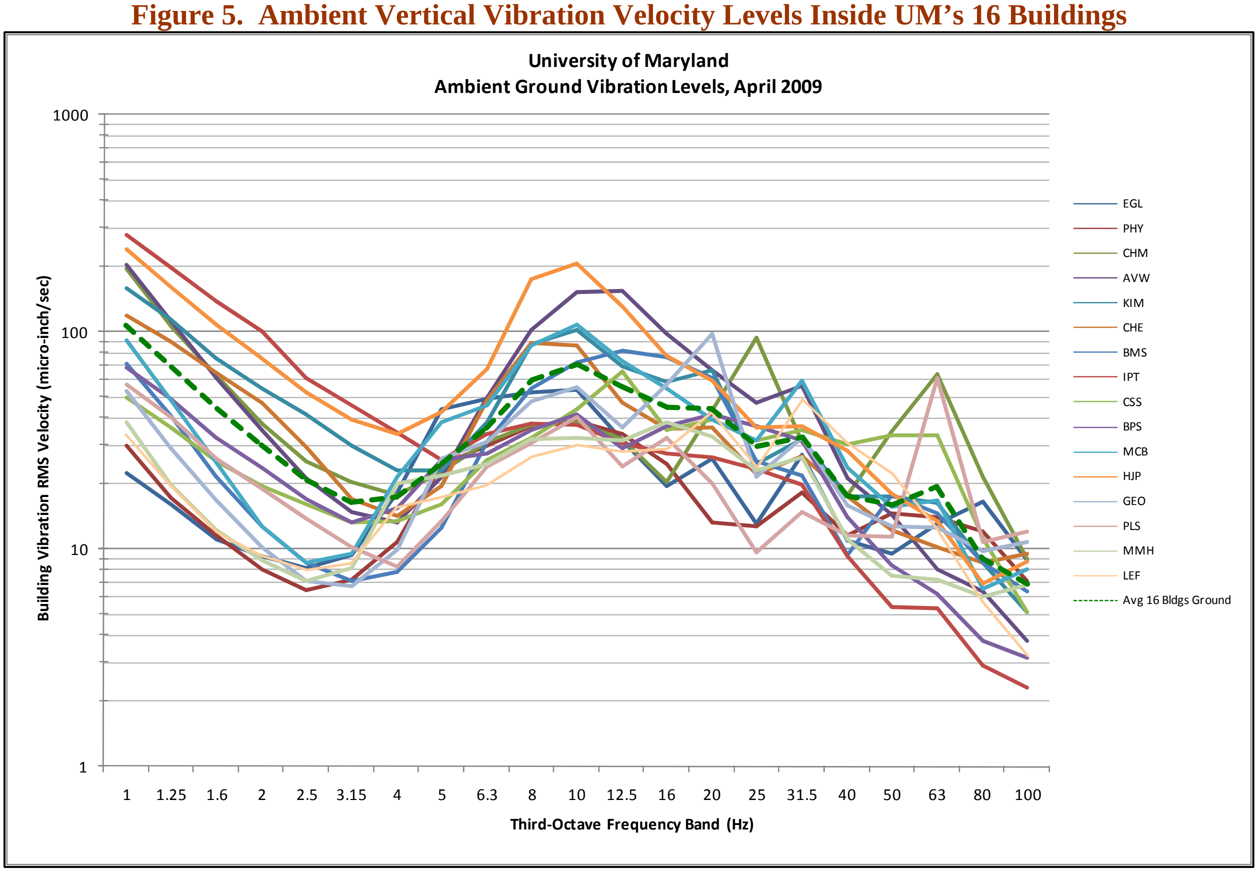


Figure 6. Ambient Vertical Vibration Velocity Levels Outside Grounds of UM's 16 Buildings

At UM's request, ambient vertical vibration measurements were also performed in two parking lots located towards the western end of the campus, specifically Parking Lots 1B and 1D. The measurements were performed using the steel stake method driven into a dirt/grass strip near the center of each parking lot. The resulting RMS vertical vibration velocity levels are shown in **Figure 7.**

It should be noted that during the measurements there were several buses and medium trucks traveling the outer perimeter of the lots, and there were automobiles driving slowly within the lots. Also of note there was active construction occurring in and around the Tawes Fine Arts Building which appeared to contribute to the vibration measurements performed in the parking lots.

The results show vibration velocity levels of several hundred micro-inches/second in the 20 Hz and 31.5 Hz third-octave bands which were likely attributable to the bus/truck passby events and the local construction activities.

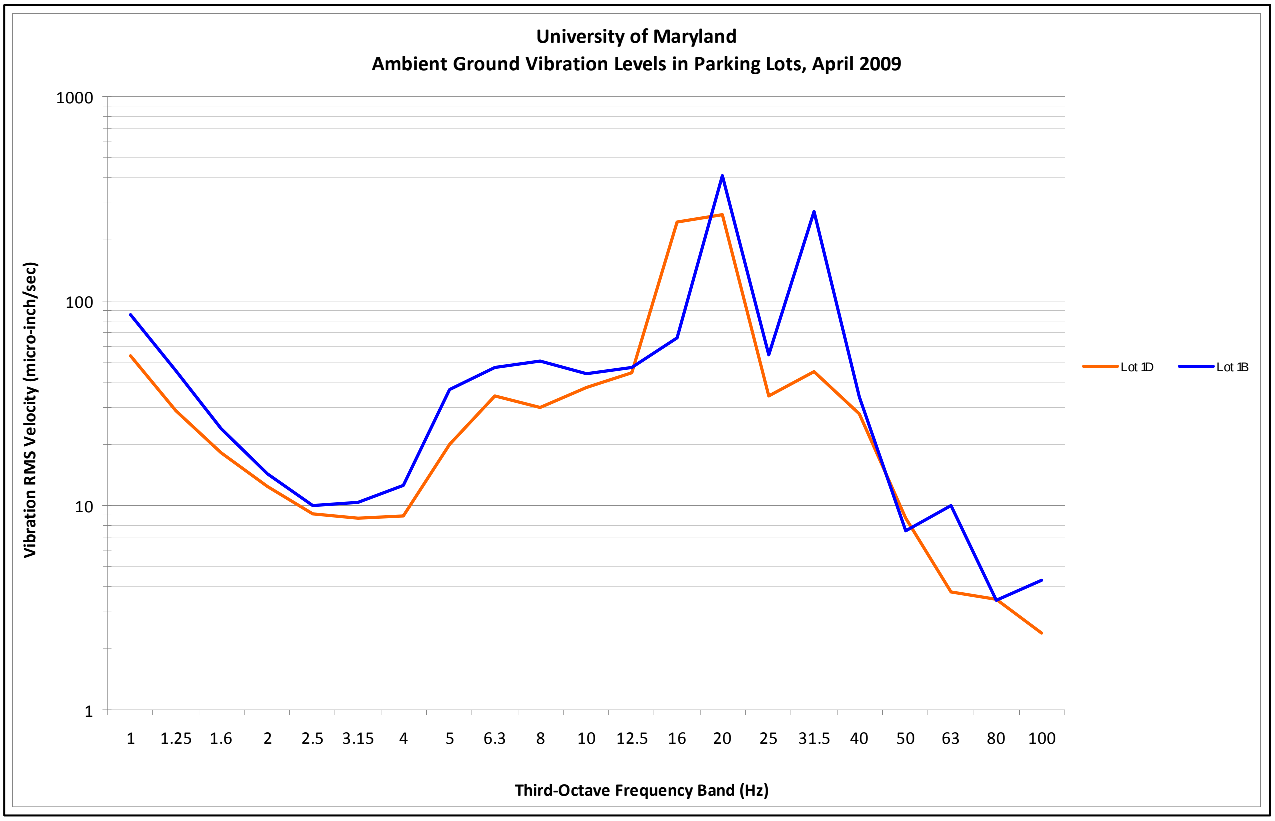


Figure 7. Ambient Vertical Vibration Velocity Levels in UM's Parking Lots

(2) Coupling Transmissibility

By performing vibration measures both inside and outside the foundations of the buildings it is possible to compare the relative difference in vibration levels between the two locations. This relationship is known as the coupling or transmission efficiency of the building relative to the ground. These results will be used as a necessary component in the next phase of the project involving the development of propagation models for predicting the effects of future Purple Line-induced vibration levels on UM's sensitive devices.

When comparing average building vibration levels to exterior grounds, as shown in **Figure 4**, the buildings tended to vibrate less than the ground in the third-octave frequency bands below 5 Hz. The buildings and the outside grounds tended to vibrate coincidently (i.e. the same) within the 5 Hz to 63 Hz bands. This pattern would be expected given the coupling/transmissibility efficiencies between the ground and the buildings. But at the higher frequency bands of 63 Hz to 100 Hz the buildings actually vibrated more than the outside grounds, indicating that vibration sources within the buildings themselves were dominating the measurements.

The results shown in **Figures 8 to 23** provide each building's vibration velocity response relative to the ground outside each building. Being a relative relationship, the results have been expressed in decibels. In general, if the results are negative (i.e. less than zero decibels) then the building is vibrating less than the outside grounds. Conversely, if the results are positive (i.e. greater than zero decibels) then the building is vibrating more than the outside grounds.

Being ambient vibration measurements, and lacking a dominant external vibration source, these results must be viewed carefully as they do not necessarily represent how future vibrations generated by Purple Line vehicles will transfer into the buildings. However, they will be useful in developing the prediction models, especially for the frequency ranges where the building is currently vibrating less than the outside grounds.

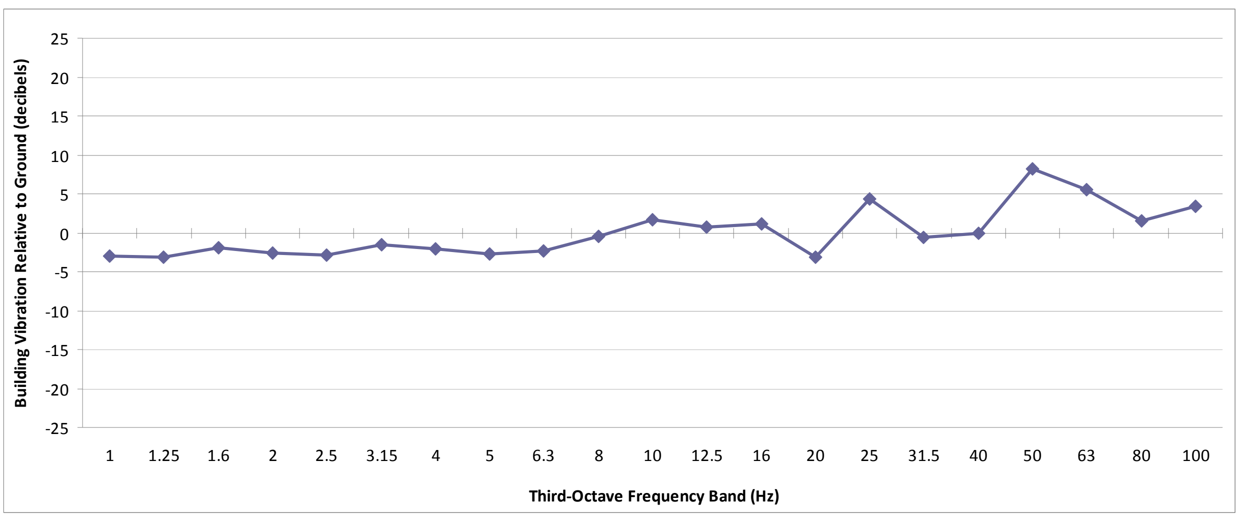


Figure 8. Building Vibration Relative to Ground for the EGL Building

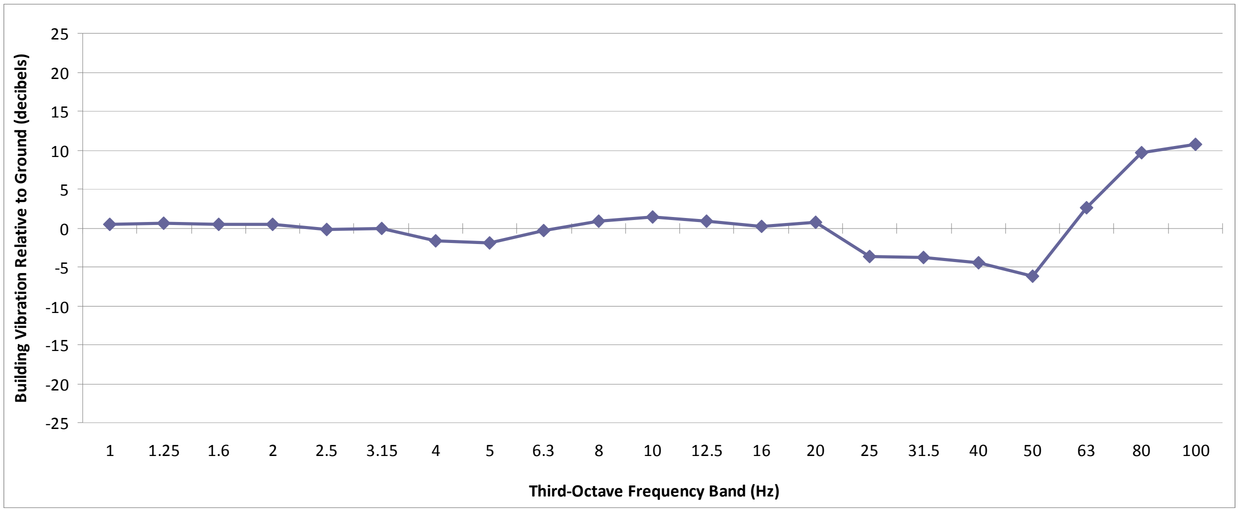


Figure 9. Building Vibration Relative to Ground for the PHY Building

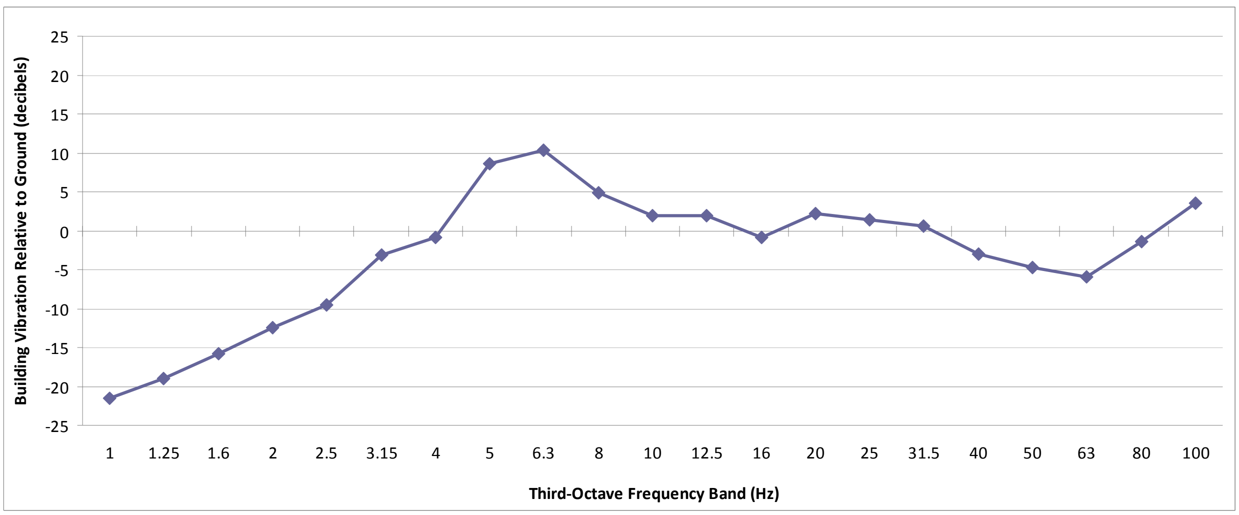


Figure 10. Building Vibration Relative to Ground for the CHM Building

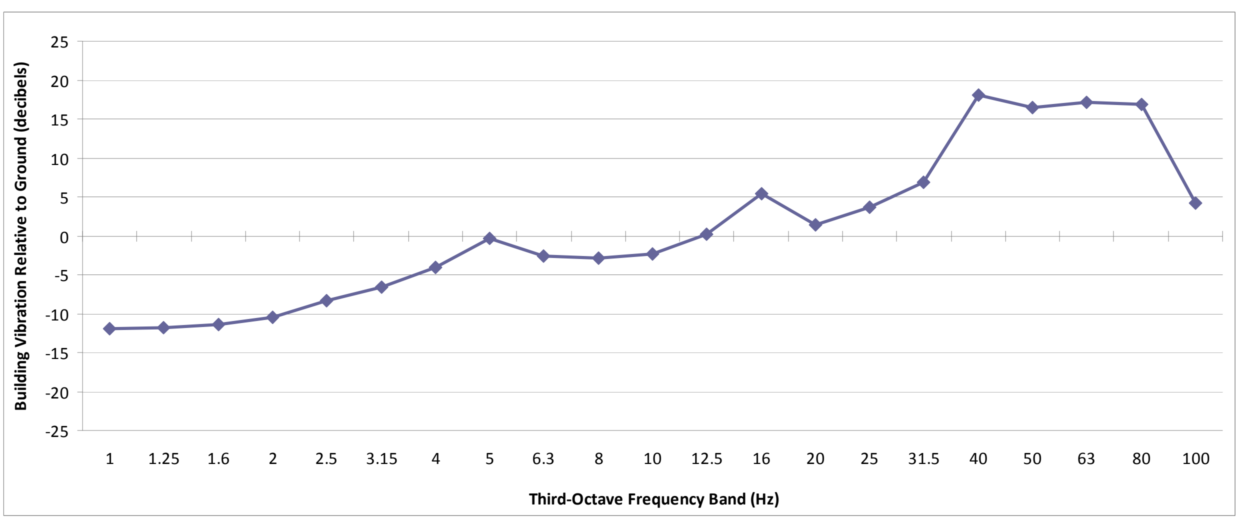


Figure 11. Building Vibration Relative to Ground for the AVW Building

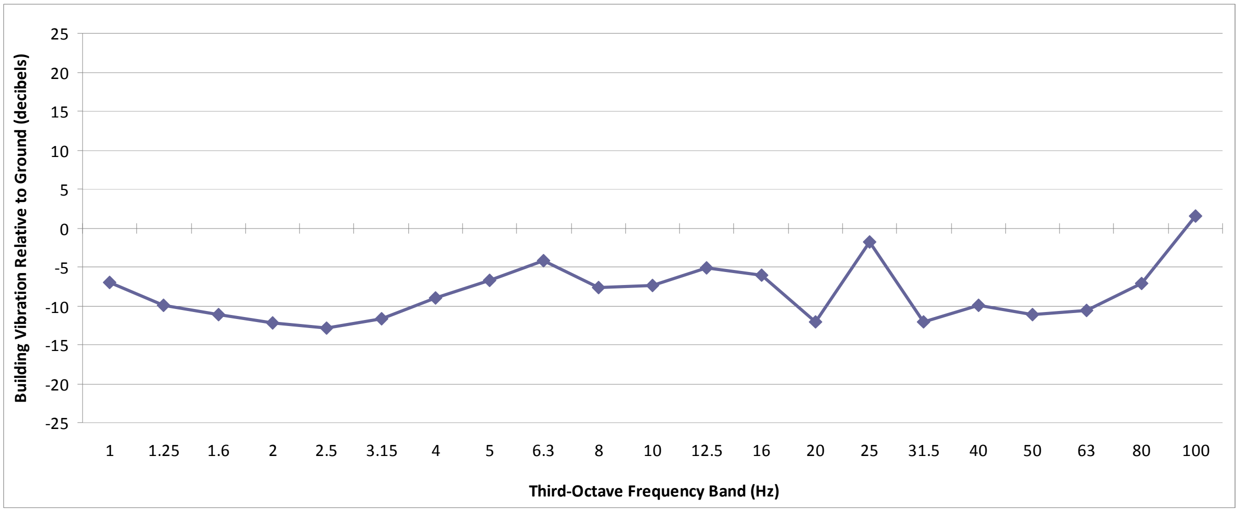


Figure 12. Building Vibration Relative to Ground for the KEB Building

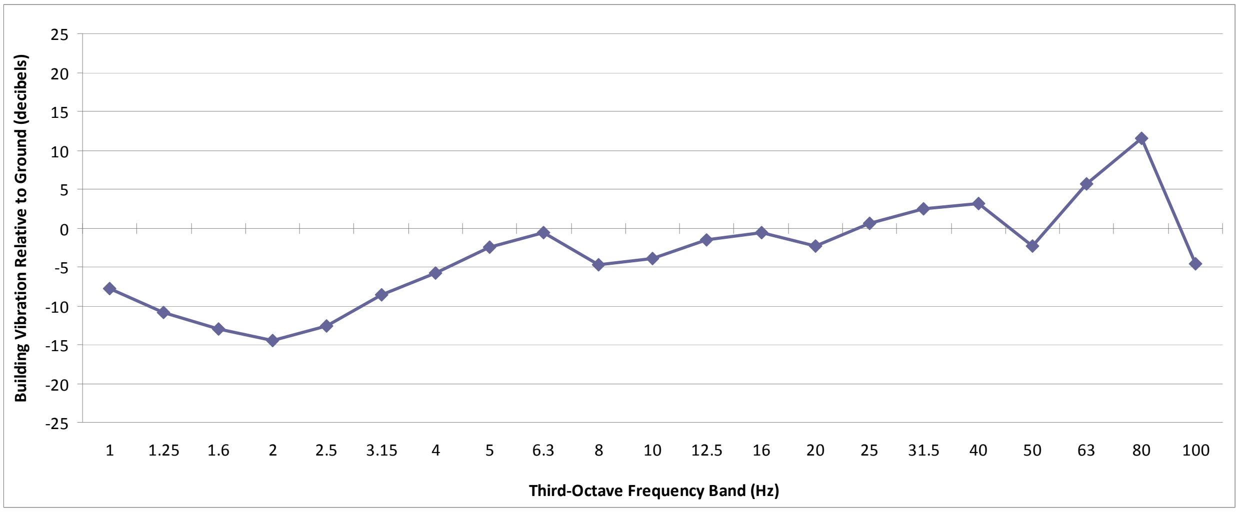


Figure 13. Building Vibration Relative to Ground for the CHE Building

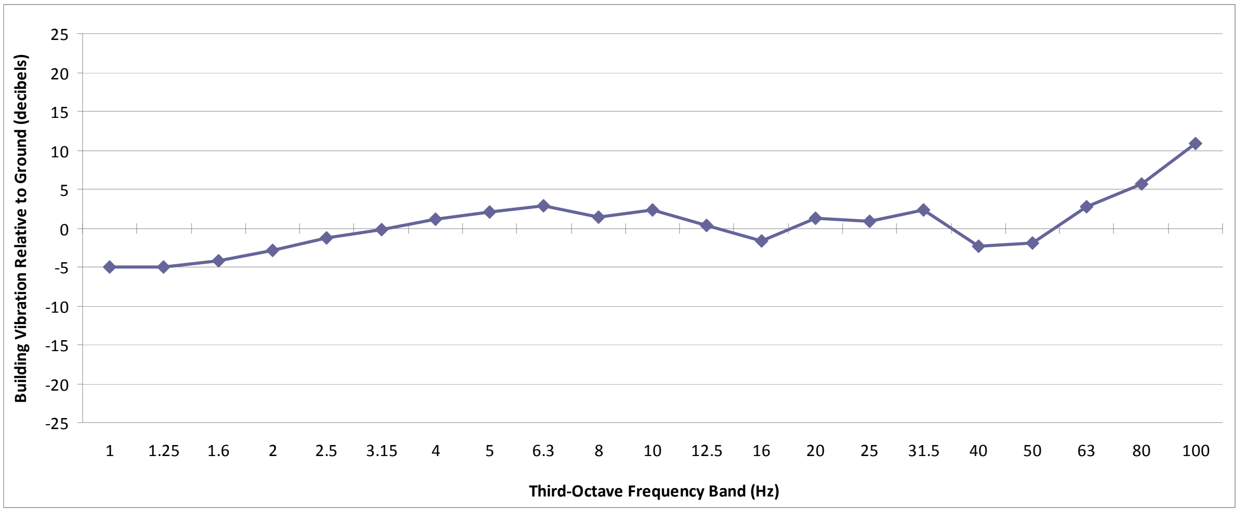


Figure 14. Building Vibration Relative to Ground for the BMS Building

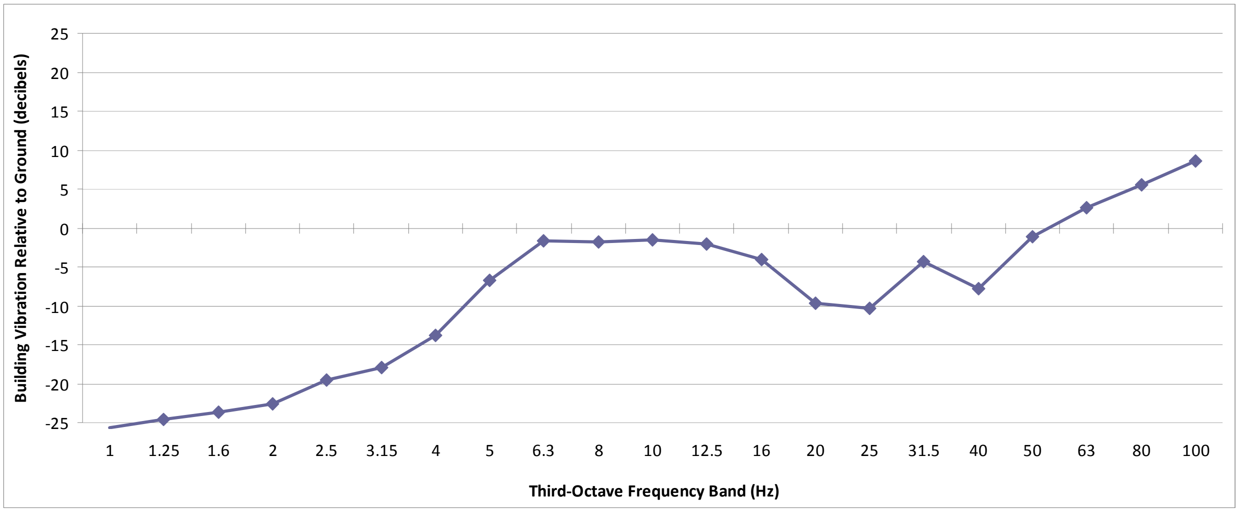


Figure 15. Building Vibration Relative to Ground for the IPT Building

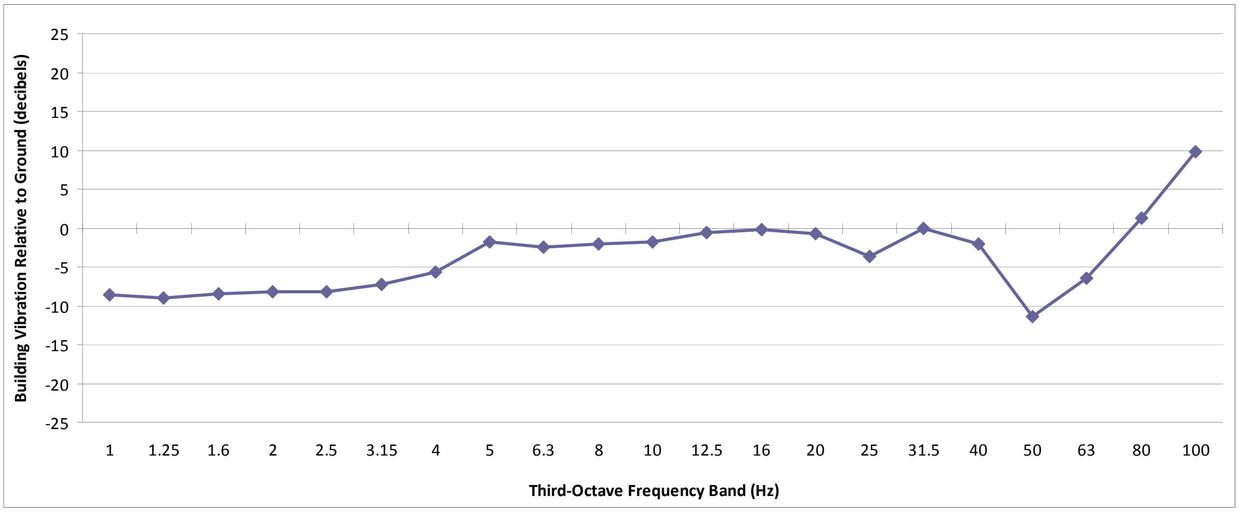


Figure 16. Building Vibration Relative to Ground for the CSS Building

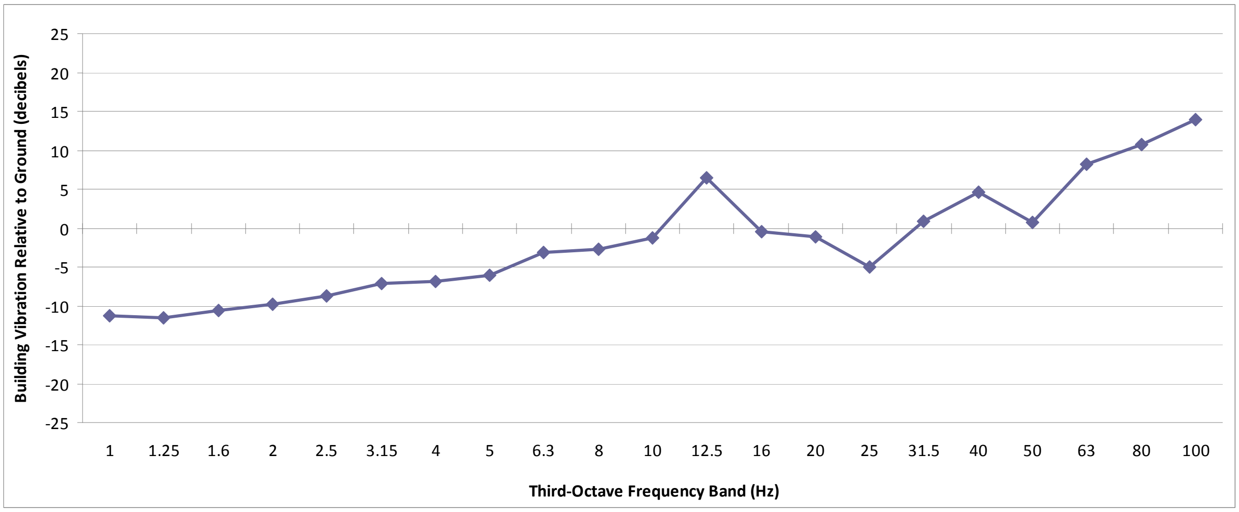


Figure 17. Building Vibration Relative to Ground for the BPS Building

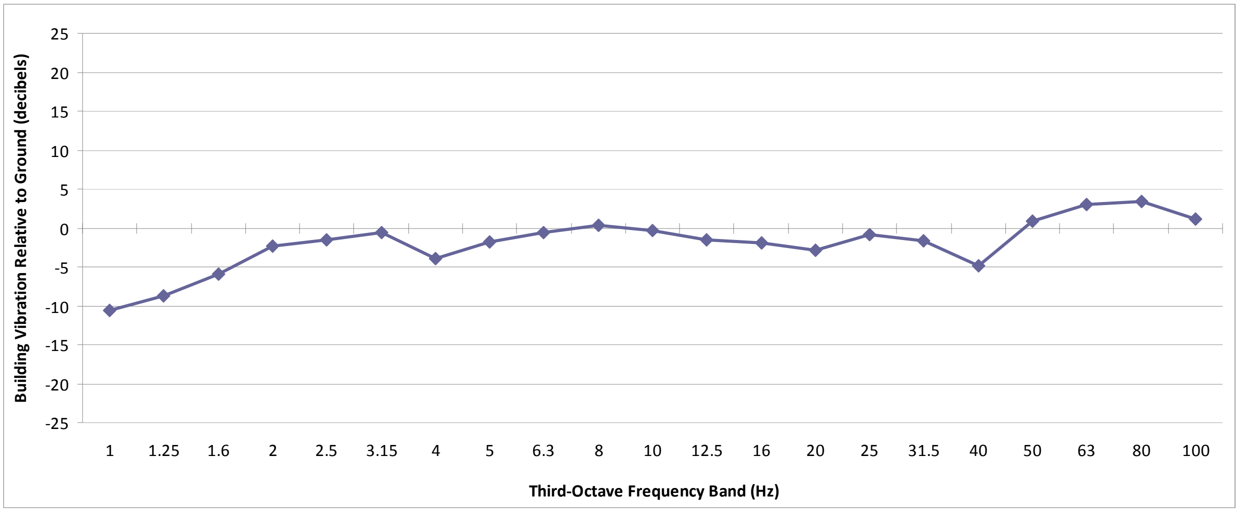


Figure 18. Building Vibration Relative to Ground for the MCB Building

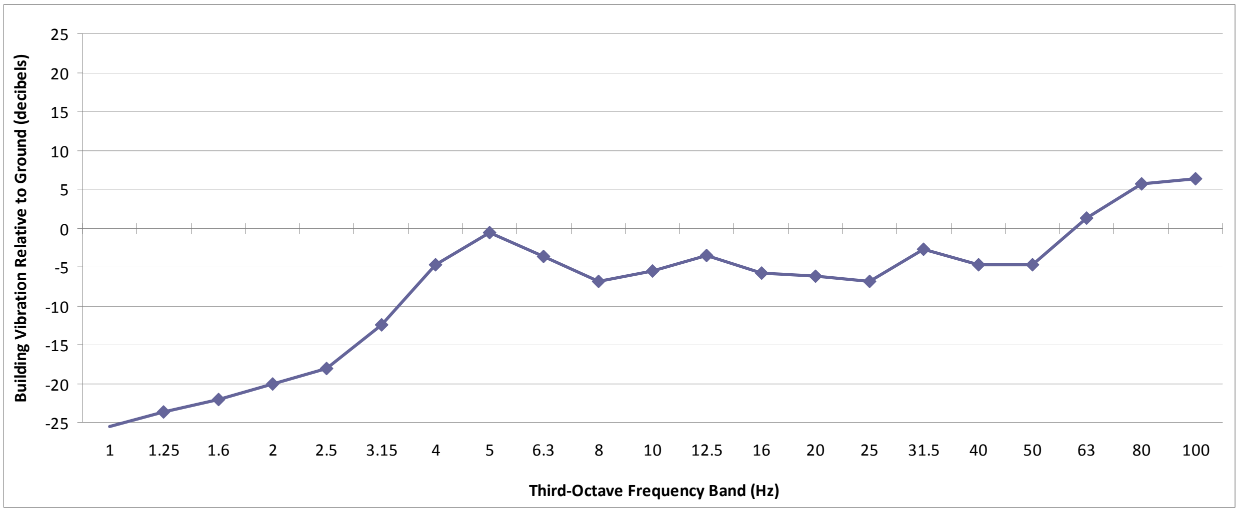


Figure 19. Building Vibration Relative to Ground for the HJP Building

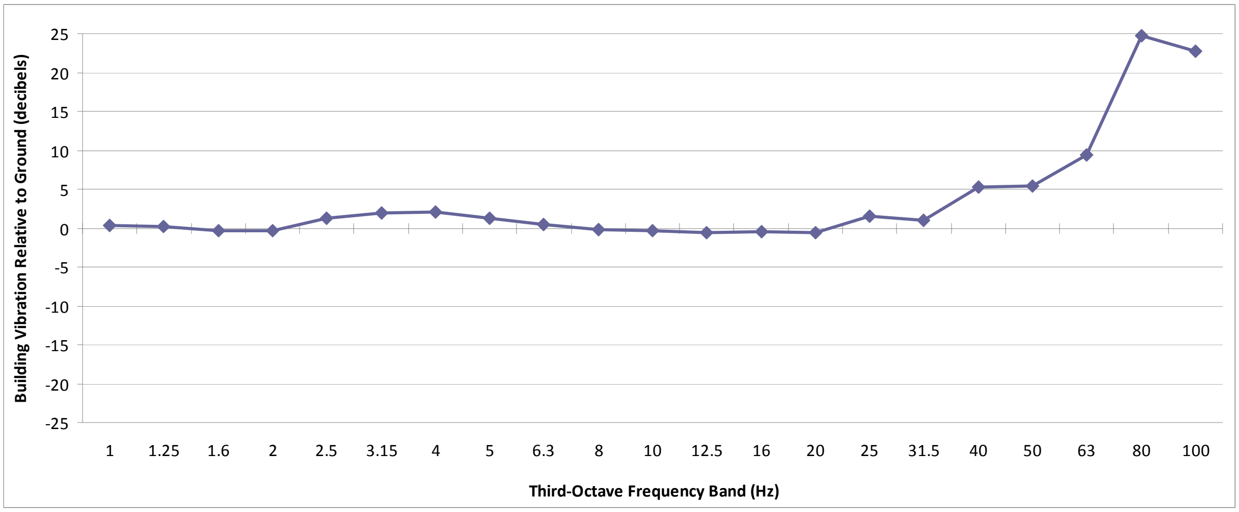


Figure 20. Building Vibration Relative to Ground for the GEO Building

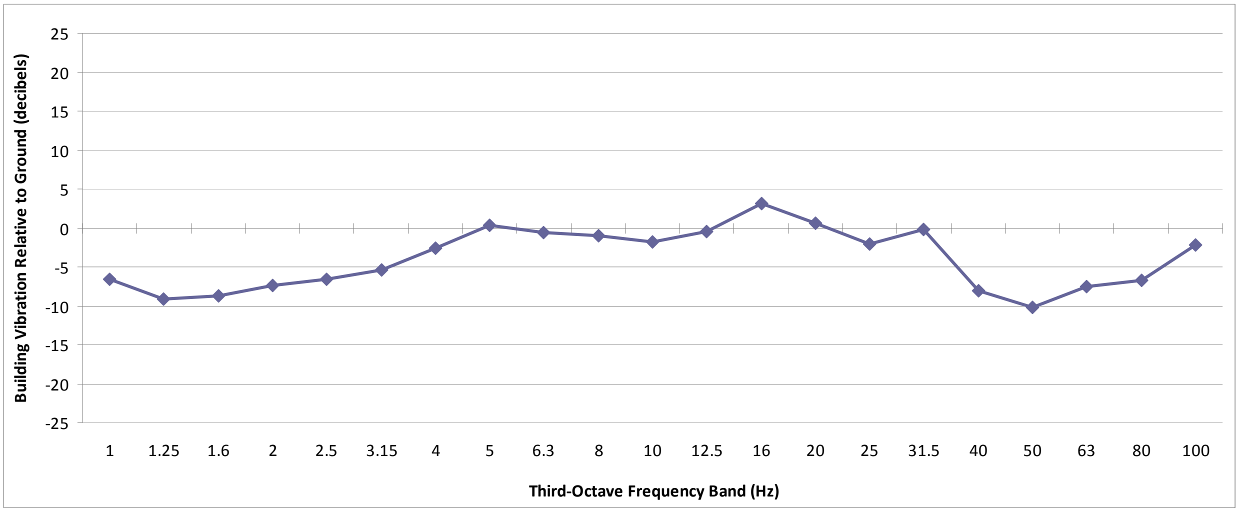


Figure 21. Building Vibration Relative to Ground for the PLS Building

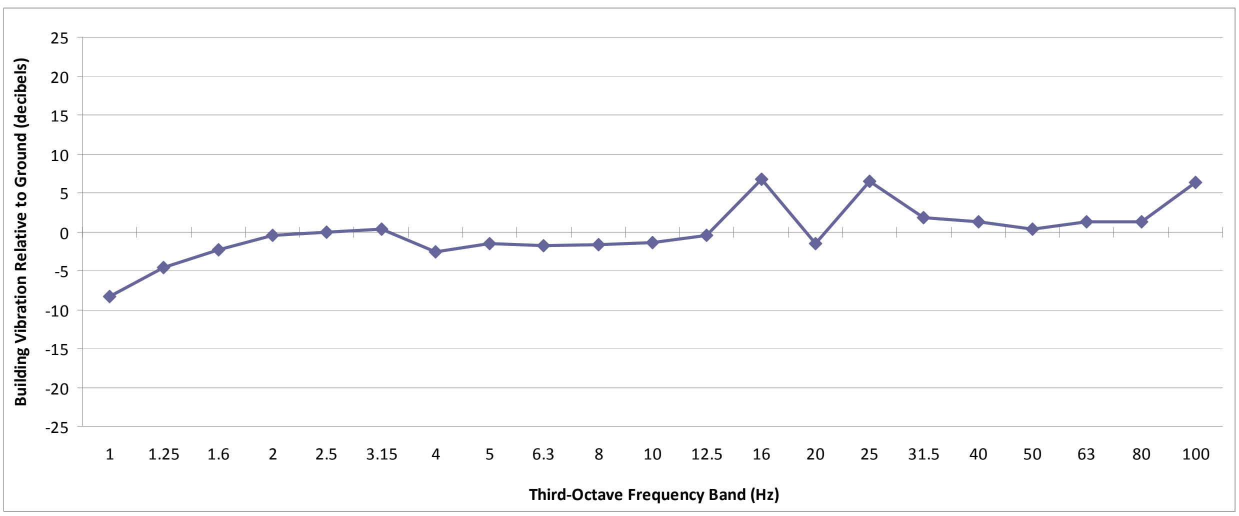


Figure 22. Building Vibration Relative to Ground for the MMH Building

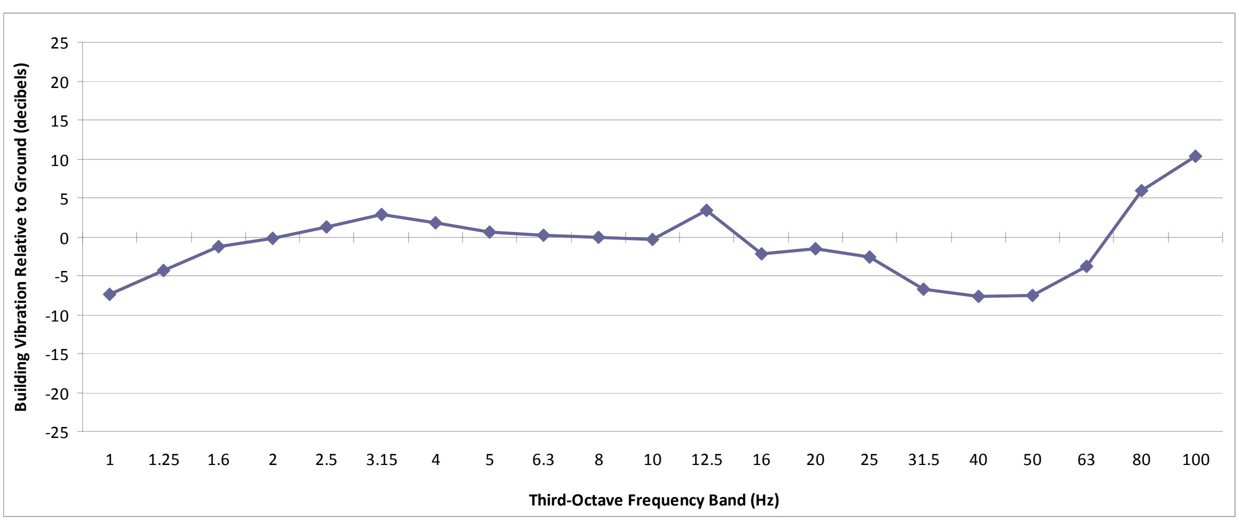


Figure 23. Building Vibration Relative to Ground for the LEF Building

(3) UM's Vibration-Sensitive Devices

As listed in **Table 4**, ambient vibration measures were also performed in the immediate vicinity of 30 vibration-sensitive laboratory devices located in various buildings on UM's campus. The instrumentation listed in **Table 2** was used for these measurements as well. As can be seen in **Figure 3**, vibration levels were measured on the floor near the devices in three mutually-orthogonal directions defined by the following convention:

- X direction – normal or latitudinal to the roadway to carry Purple Line or bus traffic
- Y direction – parallel or longitudinal to the roadway to carry Purple Line or bus traffic
- Z direction – vertical direction

Table 4. Vibration Measurements Near Sensitive Devices

Building - Abbrev. - No.	Room	Sensitive Device
Engineering - EGL - 089	122	Dynamic Material Analyzer/MTS Tytron 250
Physics Bldg - PHY - 082	1357	SQUID 1/SQUID 2
Physics Bldg - PHY - 082	2317	Room 2317
Kim Engineering - KEB - 225	Clean Room 2nd Floor	Direct Writing E Beam System
AV Williams - AVW - 115	1324	Cryogenic System, pneumatic system
Kim Engineering - KEB - 225	1237C	X-ray, Field Emission Electron Microscope
Kim Engineering - KEB - 225	1237B	Hitachi SU-70 SEM
Chemistry - CHM - 091	B0128	Nuclear Magnetic Resonance
Chemistry - CHM - 091	B0117	Room B0117
Computer Space Sciences - CCS - 224	B0223	Laser on table, pneumatic isolation
Computer Space Sciences - CCS - 224	B0213	Laser on table, pneumatic isolation
Marie Mount Hall - MMH - 046	3416K	Brain Wave Research
Energy Research Facility - ERF - 223	202	Room 202 - No Sensitive Equipment
Microbiology - MCB - 231	0207E	SEM Room
Engineering - EGL - 089	0128 CALCE Lab	CALCE Lab
Engineering - EGL - 089	1177	Room 1177
Physics - PHY - 082	2219	Room 2219
Physics - PHY - 082	2321	JEOL JSPM-4500A
Kim Engineering - KEB - 225	SubFab Mech. Rm	Subfab Mech. Room - No Sensitive Equipment
AV Williams - AVW - 115	1322	Electron Beam
Kim Engineering - KEB - 225	1237D	JEOL JXA-8900R WD/ED, Micro Analyzer
Kim Engineering - KEB - 225	Adjacent to Rm 1237B	Transmission Electron Microscope
Chemistry - CHM - 091	B0127	X-ray Photoelectron Spectroscopy Center
Chemistry - CHM - 091	B0112	X-ray Crystallography
Biosciences Research - BPS - 144	1205&1203	Compound and Laser Scanning Microscope
Computer Space Sciences - CCS - 224	B0202	Quantum Information ion trap
Marie Mount Hall - MMH - 046	Ground Floor Rm 400	Room 400
Energy Research Facility - ERF - 223	202B	Scanning Electron Microscope
Biomolecular Sciences - BMS - 413	1116	X-ray (produces vibration)
Microbiology - MCB - 231	0107F TEM Room	Convolution Microscope

Fifteen minute vibration acceleration data samples were recorded at each measurement location in orthogonal directions using three PCB 393B05 accelerometers (10 V/g) mounted to seismic blocks with the data streaming into multi-channel RION DA-20 data recorders. The data was later replayed and analyzed one channel at a time using a Norsonics NOR-140 analyzer configured for third-octave bands from 1 Hz to 100 Hz. The data was then transferred to Excel spreadsheets where a numerical integration was performed to yield vibration velocity levels in units of micro-inches/second.

Figure 24 provides the results for RMS vibration velocity levels measured near UM's sensitive devices in the X direction, normal to the nearest roadway. Each particular measurement location has its own unique results, however, after an initial increase in the 3.15 Hz band region, the vibration velocity levels, in general, decrease with higher frequency. The majority of the low frequency vibration levels ranged between 10 and 100 micro-inches/second, and decreased by an order of magnitude down to the 1 to 10 micro-inches/second range at higher frequencies.

Figure 25 provides the results for RMS vibration velocity levels measured near UM's sensitive devices in the Y direction, parallel to the nearest roadway. Each particular measurement location has its own unique results, however, after an initial increase in the 3.15 Hz band region, the vibration velocity levels, in general, decrease with higher frequency. The majority of the low frequency vibration levels ranged between 10 and 100 micro-inches/second, and decreased by an order of magnitude down to the 1 to 10 micro-inches/second range at higher frequencies.

Figure 26 provides the results for RMS vibration velocity levels measured near UM's sensitive devices in the vertical Z direction. Each particular measurement location has its own unique results, however, after an initial decrease in the 3.15 Hz band region, the vibration velocity levels, in general, tend to increase to maximum levels in the 6.3 Hz to 40 Hz band region before steadily decreasing with higher frequencies. The majority of the vibration levels across the entire spectrum generally ranged between 10 and 100 micro-inches/second, with several results elevating by an order of magnitude into the 100 to 1,000 micro-inches/second range in the mid-frequency bands. In general, the vibration velocity levels in the vertical (Z) direction were notably higher than in either the latitudinal (X) or longitudinal (Y) directions.

Appendix A contains tabulated summaries for all vibration levels presented in this report.

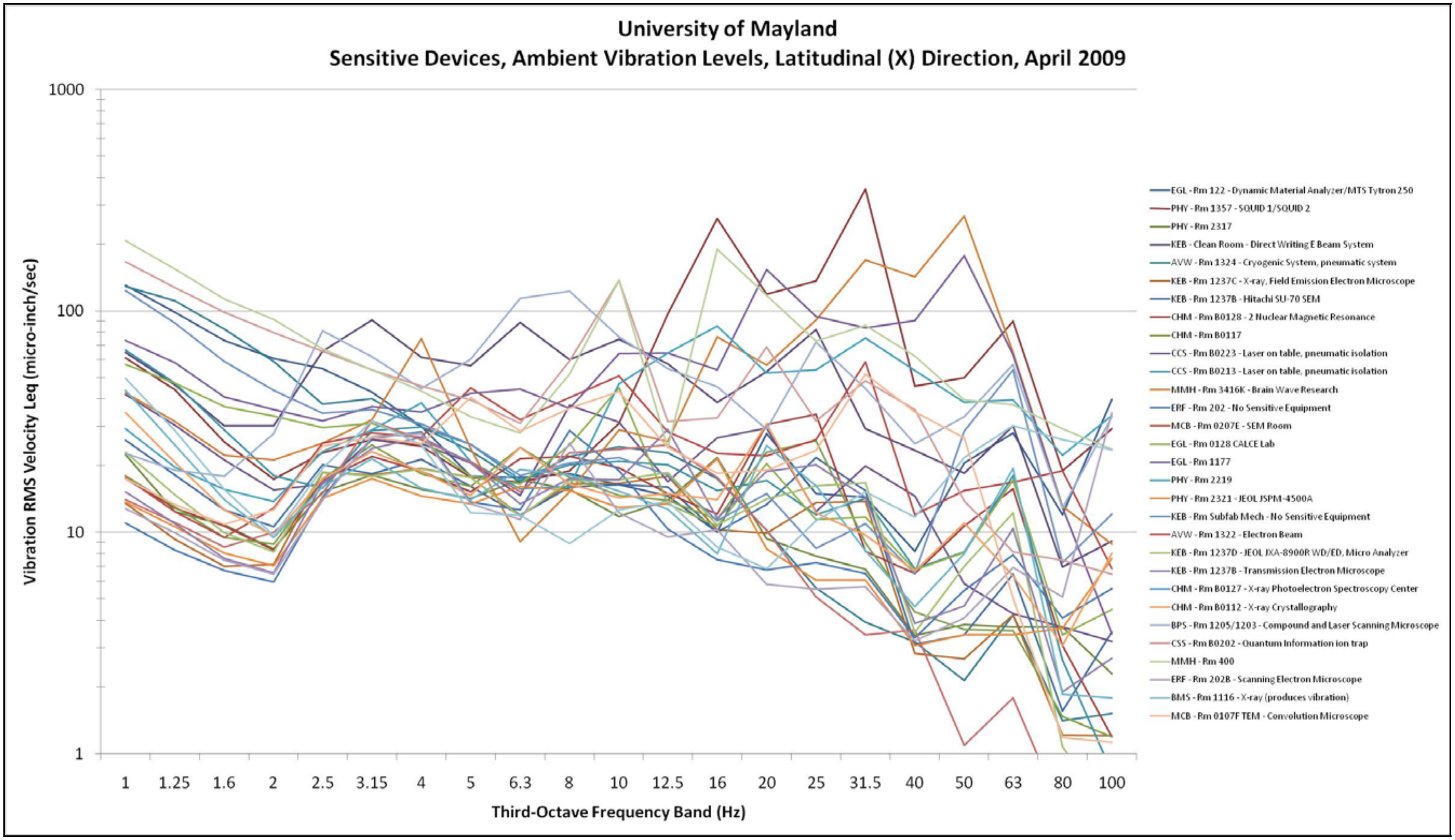


Figure 24. Ambient Vibration Levels for Sensitive Devices (X direction, normal to roadway)

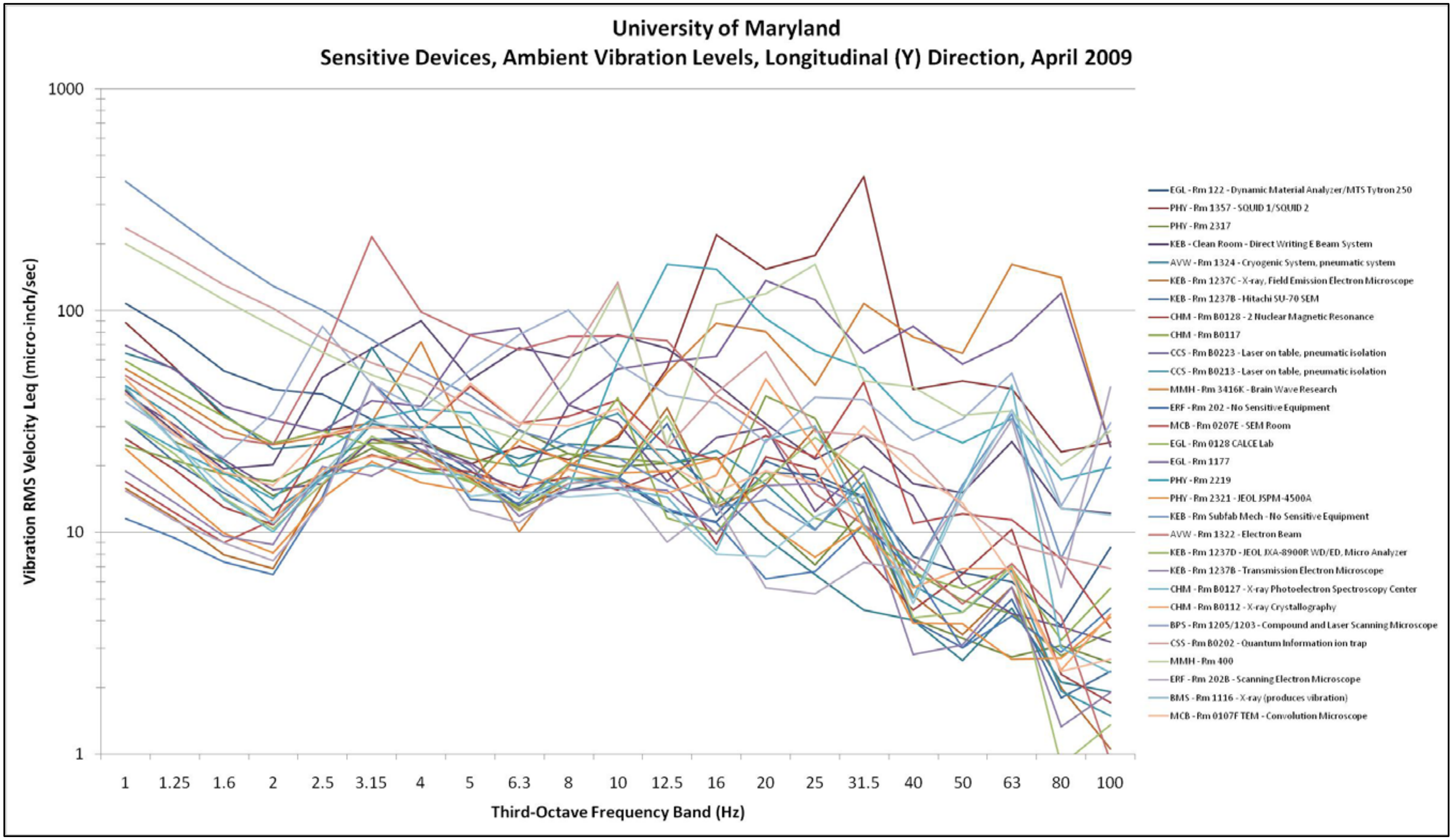


Figure 25. Ambient Vibration Levels for Sensitive Devices (Y direction, parallel to roadway)

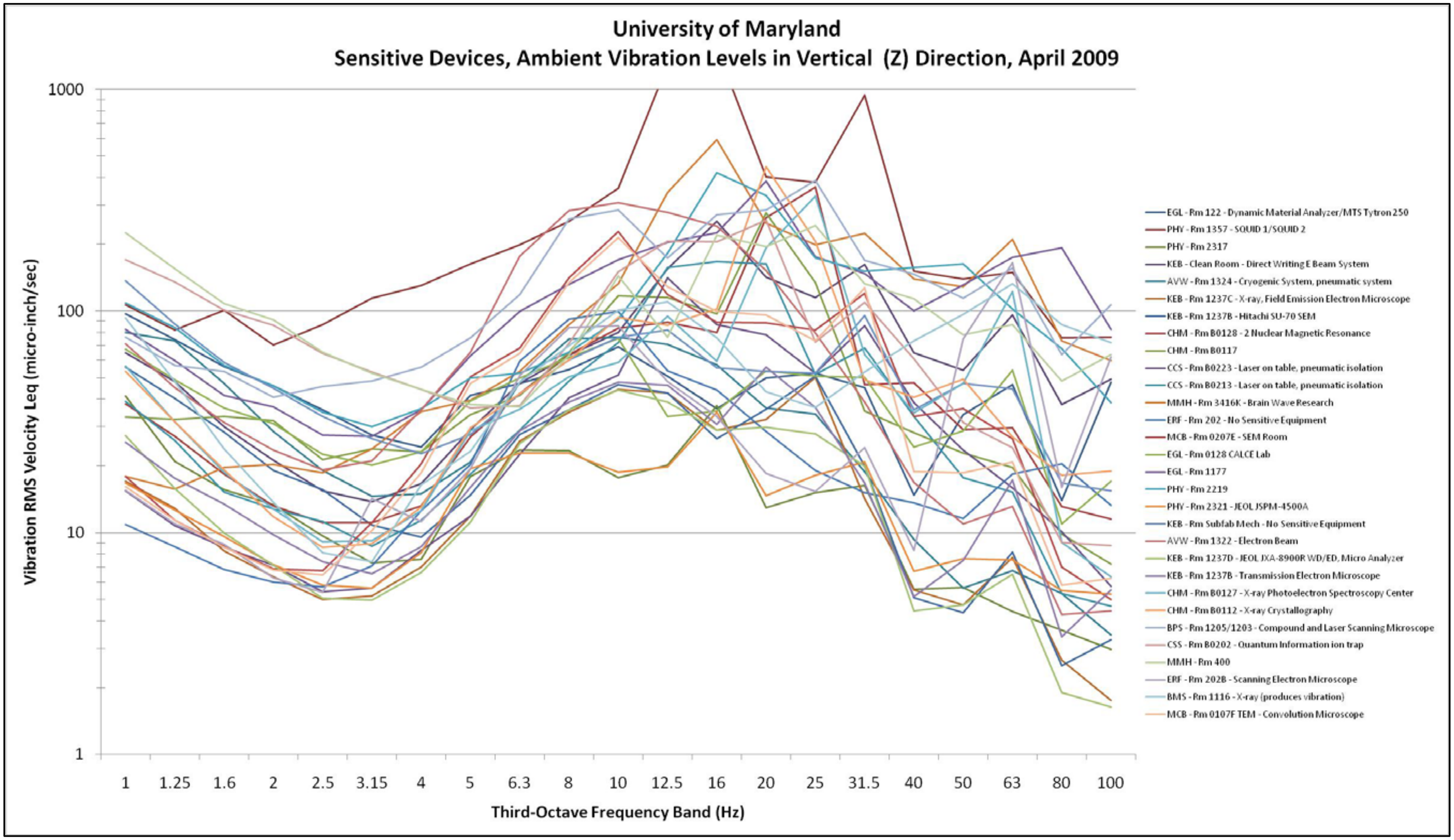


Figure 26. Ambient Vibration Levels for Sensitive Devices (Z direction, vertical)

Appendix A

Tabulated Summaries of Vibration Data Results

Engineer	Date	Building	Room	Building Interior or Exterior Grounds	Z Direction - Vibration Velocity Lfeq Levels, micro-inches/second																				
					Third-Octave Frequency Band (Hz)																				
					1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100
ET	4/28/2009	EGL	Rm 0128	Building Interior	16	11	9	7	6	8	15	32	38	50	66	34	22	18	22	25	11	24	25	20	13
ET	4/28/2009	EGL	Ground	Exterior Grounds	22	16	11	9	8	9	18	44	49	53	54	31	20	26	13	27	11	9	13	16	9
ET	4/28/2009	PHY	Rm 0113	Building Interior	31	18	12	9	6	7	9	19	29	41	45	37	25	15	8	12	7	7	19	37	24
ET	4/28/2009	PHY	Ground	Exterior Grounds	30	17	11	8	6	7	11	24	30	37	39	34	25	13	13	18	12	15	14	12	7
ET	4/28/2009	CHM	Rm B0129C	Building Interior	16	12	10	9	8	14	16	61	103	65	48	40	18	56	110	34	13	20	32	18	13
ET	4/28/2009	CHM	Ground	Exterior Grounds	195	107	63	38	25	20	18	23	31	37	38	32	20	43	94	31	18	35	64	21	9
ET	4/28/2009	AVW	Rm 1241	Building Interior	51	29	17	11	8	7	8	21	37	74	116	159	183	78	73	124	171	97	58	44	6
ET	4/28/2009	AVW	Ground	Exterior Grounds	203	112	62	36	21	15	13	22	50	102	151	154	98	66	47	56	21	14	8	6	4
ET	4/28/2009	KEB	Lobby	Building Interior	71	36	21	13	9	8	8	11	24	36	43	38	29	16	20	8	6	5	5	4	6
ET	4/28/2009	KEB	Ground	Exterior Grounds	159	114	76	55	42	30	23	23	38	88	102	69	59	66	25	32	18	17	16	9	5
ET	4/28/2009	CHE	Rm 1111	Building Interior	48	26	15	9	7	6	7	15	45	51	55	40	33	28	24	35	25	9	19	32	6
ET	4/28/2009	CHE	Ground	Exterior Grounds	119	90	65	47	30	17	14	19	48	88	87	47	36	36	22	27	17	12	10	9	10
ET	4/28/2009	BMS	Rm 1120	Building Interior	40	23	13	9	7	7	9	16	44	65	94	84	63	71	28	28	7	14	20	17	22
ET	4/28/2009	BMS	Ground	Exterior Grounds	71	41	22	13	9	7	8	13	31	55	72	81	77	62	25	22	9	18	15	9	6
ET	4/29/2009	IPT	Rm B0112	Building Interior	15	12	9	7	6	6	7	12	28	31	31	24	17	9	7	12	4	5	7	6	6
ET	4/29/2009	IPT	Ground	Exterior Grounds	281	198	137	101	61	46	34	26	34	38	37	31	27	27	23	20	9	5	5	3	2
ET	4/29/2009	CSS	Rm B0213	Building Interior	19	13	10	8	6	6	7	13	19	26	36	61	35	36	21	35	24	9	16	13	16
ET	4/29/2009	CSS	Ground	Exterior Grounds	50	36	25	20	16	13	13	16	26	33	44	65	35	40	32	35	30	34	34	11	5
ET	4/29/2009	BPS	Bathroom	Building Interior	19	13	10	8	6	6	7	13	19	26	36	61	35	36	21	35	24	9	16	13	16
ET	4/29/2009	BPS	Ground	Exterior Grounds	68	49	33	24	17	13	15	26	28	35	42	29	37	42	37	32	14	8	6	4	3
ET	4/29/2009	MCB	Rm 0107G	Building Interior	27	18	13	10	7	9	14	31	43	90	103	62	44	28	29	50	14	17	24	10	9
ET	4/29/2009	MCB	Ground	Exterior Grounds	91	49	25	13	9	10	21	38	46	87	108	74	55	39	32	60	24	16	17	7	8
ET	4/29/2009	HJP	Rm 0109	Building Interior	13	10	9	7	7	9	20	40	44	80	108	87	40	29	17	27	16	10	16	13	18
ET	4/29/2009	HJP	Ground	Exterior Grounds	242	160	108	75	53	39	34	43	68	175	205	131	78	60	36	37	28	18	14	7	9
ET	4/29/2009	GEO	Rm 1101	Building Interior	55	30	16	10	8	8	13	30	33	47	54	34	54	92	26	37	29	24	37	170	148
ET	4/29/2009	GEO	Ground	Exterior Grounds	54	29	17	10	7	7	10	26	31	48	56	36	57	98	21	32	16	13	12	10	11
ET	4/29/2009	PLS	Rm 0114	Building Interior	27	14	10	8	6	5	6	14	22	28	33	23	46	22	8	15	5	4	26	5	9
ET	4/29/2009	PLS	Ground	Exterior Grounds	57	40	26	19	14	10	8	13	24	31	41	24	32	20	10	15	11	11	61	11	12
ET	4/30/2009	MMH	Rm 1314	Building Interior	15	12	9	8	7	9	15	18	20	26	28	30	83	28	48	33	13	8	8	7	14
ET	4/30/2009	MMH	Ground	Exterior Grounds	38	20	12	9	7	8	20	22	25	32	32	32	38	33	23	27	11	8	7	6	7
ET	4/30/2009	LEF	Rm 0101	Building Interior	14	12	10	9	9	12	19	19	20	27	29	41	22	36	18	23	13	9	8	11	11
ET	4/30/2009	LEF	Ground	Exterior Grounds	34	20	12	9	8	9	16	17	20	27	30	28	29	43	24	49	31	22	13	6	3
ET	4/30/2009	Parking Lot 1D	Ground	Exterior Grounds	54	29	18	12	9	9	9	20	34	30	38	44	243	265	34	45	28	9	4	3	2
ET	4/30/2009	Parking Lot 1D	Ground	Exterior Grounds	54	29	18	12	9	9	9	20	34	30	38	44	243	265	34	45	28	9	4	3	2
ET	4/30/2009	Parking Lot 1B	Ground	Exterior Grounds	86	46	24	14	10	10	12	37	47	51	44	47	66	408	55	274	34	8	10	3	4
ET	4/30/2009	Parking Lot 1B	Ground	Exterior Grounds	86	46	24	14	10	10	12	37	47	51	44	47	66	408	55	274	34	8	10	3	4

Engineer	Date	Building	Direction		Building Vibration Relative to Ground, decibels																				
					Third-Octave Frequency Band (Hz)																				
					1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100
ET	4/28/2009	EGL	Z		-3.0	-3.2	-1.9	-2.6	-2.9	-1.6	-2.0	-2.7	-2.3	-0.5	1.7	0.7	1.1	-3.2	4.4	-0.6	-0.1	8.2	5.5	1.5	3.4
ET	4/28/2009	PHY	Z		0.4	0.6	0.5	0.4	-0.2	-0.1	-1.6	-1.9	-0.3	0.9	1.4	0.8	0.2	0.8	-3.6	-3.8	-4.5	-6.2	2.6	9.7	10.7
ET	4/28/2009	CHM	Z		-21.6	-18.9	-15.8	-12.5	-9.6	-3.1	-0.8	8.6	10.4	4.9	2.0	2.0	-0.9	2.3	1.3	0.6	-3.0	-4.7	-5.9	-1.3	3.5
ET	4/28/2009	AVW	Z		-11.9	-11.8	-11.4	-10.4	-8.3	-6.5	-4.1	-0.4	-2.5	-2.8	-2.3	0.3	5.5	1.4	3.7	6.8	18.1	16.5	17.1	16.8	4.2
ET	4/28/2009	KEB	Z		-7.0	-9.9	-11.1	-12.2	-12.9	-11.7	-9.0	-6.7	-4.2	-7.6	-7.4	-5.1	-6.0	-12.1	-1.9	-12.1	-9.9	-11.1	-10.7	-7.1	1.5
ET	4/28/2009	CHE	Z		-7.9	-10.9	-13.0	-14.4	-12.6	-8.6	-5.9	-2.5	-0.6	-4.7	-4.0	-1.5	-0.7	-2.3	0.7	2.4	3.1	-2.4	5.6	11.5	-4.6
ET	4/28/2009	BMS	Z		-5.0	-5.0	-4.2	-2.8	-1.2	-0.2	1.1	2.1	2.9	1.4	2.3	0.3	-1.7	1.3	0.8	2.3	-2.3	-1.9	2.7	5.7	10.9
ET	4/29/2009	IPT	Z		-25.7	-24.6	-23.6	-22.6	-19.5	-18.0	-13.8	-6.8	-1.7	-1.8	-1.5	-2.1	-4.1	-9.7	-10.4	-4.3	-7.9	-1.1	2.6	5.5	8.6
ET	4/29/2009	CSS	Z		-8.6	-9.0	-8.5	-8.2	-8.2	-7.2	-5.6	-1.9	-2.5	-2.0	-1.8	-0.6	-0.2	-0.7	-3.6	-0.1	-2.1	-11.4	-6.4	1.3	9.7
ET	4/29/2009	BPS	Z		-11.3	-11.5	-10.7	-9.8	-8.8	-7.2	-6.9	-6.0	-3.1	-2.7	-1.3	6.4	-0.5	-1.2	-4.9	0.9	4.6	0.7	8.2	10.7	13.9
ET	4/29/2009	MCB	Z		-10.6	-8.8	-5.9	-2.3	-1.5	-0.5	-3.9	-1.8	-0.5	0.3	-0.4	-1.5	-1.9	-2.9	-0.8	-1.6	-4.9	0.8	3.0	3.4	1.2
ET	4/29/2009	HJP	Z		-25.6	-23.7	-22.0	-20.1	-18.1	-12.4	-4.7	-0.6	-3.7	-6.9	-5.6	-3.5	-5.7	-6.2	-6.8	-2.8	-4.7	-4.7	1.3	5.6	6.3
ET	4/29/2009	GEO	Z		0.3	0.3	-0.3	-0.4	1.2	2.0	2.0	1.3	0.4	-0.2	-0.3	-0.6	-0.5	-0.5	1.6	1.1	5.2	5.4	9.4	24.8	22.7
ET	4/29/2009	PLS	Z		-6.6	-9.1	-8.7	-7.4	-6.5	-5.4	-2.6	0.4	-0.6	-0.9	-1.9	-0.5	3.1	0.6	-2.0	-0.2	-8.1	-10.1	-7.6	-6.8	-2.2
ET	4/30/2009	MMH	Z		-8.3	-4.5	-2.4	-0.5	0.0	0.3	-2.6	-1.5	-1.8	-1.6	-1.4	-0.5	6.7	-1.5	6.4	1.8	1.2	0.4	1.3	1.2	6.3
ET	4/30/2009	LEF	Z		-7.4	-4.3	-1.2	-0.2	1.2	2.9	1.8	0.6	0.2	-0.1	-0.3	3.3	-2.2	-1.5	-2.6	-6.7	-7.7	-7.6	-3.8	5.9	10.3

Engineer	Date	Building	Room	Sensitive Instrument	X Direction - Vibration Velocity Lfeq Levels, micro-inches/second																				
					Third-Octave Frequency Band (Hz)																				
					1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100
SBH	4/28/2009	Engineering - 089	122	EGL - Rm 122 - Dynamic Material Analyzer/MTS Tytron 250	131	99	74	61	55	43	30	18	18	18	16	15	10	28	15	14	8	21	28	12	40
SBH	4/28/2009	Physics Bldg - 082	1357	PHY - Rm 1357 - SQUID 1/SQUID 2	61	44	26	17	23	26	25	18	17	19	31	97	262	119	136	354	46	50	90	19	29
SBH	4/28/2009	Physics Bldg - 082	2317	PHY - Rm 2317	22	12	11	8	15	18	16	14	17	16	12	14	22	9	8	7	3	4	4	4	2
SBH	4/28/2009	Kim Engineering - 225	Clean Room 2nd Floor	KEB - Clean Room - Direct Writing E Beam System	65	46	30	30	66	91	62	57	89	60	74	58	39	53	82	29	23	19	30	7	9
SBH	4/28/2009	AV Williams - 115	1324	AVW - Rm 1324 - Cryogenic System, pneumatic system	129	111	83	59	38	40	30	23	17	22	24	23	17	10	6	4	3	2	4	1	2
SBH	4/28/2009	Kim Engineering - 225	1237C	KEB - Rm 1237C - X-ray, Field Emission Electron Microscop	14	9	7	7	19	18	19	18	12	17	17	18	10	10	14	14	3	3	4	1	1
SBH	4/28/2009	Kim Engineering - 225	1237B	KEB - Rm 1237B - Hitachi SU-70 SEM	26	18	13	11	20	18	21	16	12	16	16	16	10	13	22	15	3	3	6	2	4
SBH	4/28/2009	Chemistry - 091	B0128	CHM - Rm B0128 - 2 Nuclear Magnetic Resonance	17	13	11	8	17	22	19	15	22	22	20	15	12	31	34	8	7	11	16	3	1
SBH	4/28/2009	Chemistry - 091	B0117	CHM - Rm B0117	18	13	10	9	18	25	18	16	24	18	15	14	11	23	26	9	4	4	4	1	1
SBH	4/29/2009	Computer Space Sciences - 224	B0223	CCS - Rm B0223 - Laser on table, pneumatic isolation	42	31	21	16	17	26	25	21	15	37	31	17	27	30	12	20	15	6	4	4	3
SBH	4/29/2009	Computer Space Sciences - 224	B0213	CCS - Rm B0213 - Laser on table, pneumatic isolation	66	47	29	18	16	29	30	25	17	20	21	20	15	17	12	14	7	8	18	3	1
SBH	4/29/2009	Marie Mount Hall - 046	3416K	MMH - Rm 3416K - Brain Wave Research	43	32	22	21	25	32	75	24	9	15	29	26	76	57	91	169	143	268	65	13	9
SBH	4/29/2009	Energy Research Facility - 223	202	ERF - Rm 202 - No Sensitive Equipment	11	8	7	6	14	27	29	14	13	29	19	10	8	7	7	7	3	5	8	4	6
SBH	4/29/2009	Microbiology - 231	0207E	MCB - Rm 0207E - SEM Room	18	12	10	13	25	28	27	45	32	41	51	29	23	22	26	59	12	15	17	19	7
JVC	4/28/2009	Engineering - 089	0128 CALCE Lab	EGL - Rm 0128 CALCE Lab	57	47	37	34	30	31	26	18	17	25	45	13	11	20	11	12	7	8	17	3	4
JVC	4/28/2009	Engineering - 089	1177	EGL - Rm 1177	74	58	41	36	32	37	35	42	44	36	64	65	54	153	94	84	90	177	63	13	3
JVC	4/28/2009	Physics - 082	2219	PHY - Rm 2219	29	20	16	14	23	29	38	21	16	16	47	65	86	53	54	76	54	39	40	22	34
JVC	4/28/2009	Physics - 082	2321	PHY - Rm 2321 - JEOL JSPM-4500A	14	11	8	7	14	18	15	13	16	15	13	13	22	8	6	6	3	3	3	4	8
JVC	4/28/2009	Kim Engineering - 225	SubFab Mech. Rm	KEB - Rm Subfab Mech - No Sensitive Equipment	124	88	59	44	35	36	31	25	18	21	22	18	11	15	8	11	7	29	54	7	12
JVC	4/28/2009	AV Williams - 115	1322	AVW - Rm 1322 - Electron Beam	14	11	9	10	15	32	26	21	15	23	24	25	18	10	5	3	4	1	2	1	1
JVC	4/28/2009	Kim Engineering - 225	1237D	KEB - Rm 1237D - JEOL JXA-8900R WD/ED, Micro Analyz	23	15	10	8	19	18	19	18	12	17	17	19	11	14	16	17	4	7	12	1	1
JVC	4/28/2009	Kim Engineering - 225	Rm Adjacent to 1237B	KEB - Rm 1237B - Transmission Electron Microscope	15	11	8	7	17	24	27	21	13	18	17	29	12	19	20	14	4	5	10	2	3
JVC	4/28/2009	Chemistry - 091	B0127	CHM - Rm B0127 - X-ray Photoelectron Spectroscopy Cent	44	25	14	9	16	22	16	14	19	18	15	13	8	25	16	8	5	8	19	2	2
JVC	4/28/2009	Chemistry - 091	B0112	CHM - Rm B0112 - X-ray Crystallography	35	21	13	10	17	23	19	15	24	17	14	15	14	31	12	10	7	11	6	3	8
JVC	4/29/2009	Biosciences Research - 144	1205&1203	BPS - Rm 1205/1203 - Compound and Laser Scanning Mic	23	19	18	28	81	62	45	61	114	123	76	55	45	29	72	45	25	33	57	13	33
JVC	4/29/2009	Computer Space Sciences - 224	B0202	CSS - Rm B0202 - Quantum Information ion trap	167	127	98	80	66	54	46	40	31	59	137	32	33	69	32	48	36	14	8	7	6
JVC	4/29/2009	Marie Mount Hall - 046	Ground Floor by Rm 400	MMH - Rm 400	207	155	113	91	67	54	44	33	28	52	137	24	190	118	73	86	62	40	38	29	24
JVC	4/29/2009	Energy Research Facility - 223	202B	ERF - Rm 202B - Scanning Electron Microscope	13	10	7	6	14	27	28	13	11	25	12	10	10	6	6	6	3	4	7	5	35
JVC	4/29/2009	Biomolecular Sciences - 413	1116	BMS - Rm 1116 - X-ray (produces vibration)	50	29	16	10	19	32	25	12	12	9	13	14	9	7	11	15	12	22	30	26	24
JVC	4/29/2009	Microbiology - 231	0107F TEM Room	MCB - Rm 0107F TEM - Convolution Microscope	17	13	11	13	24	27	25	41	29	36	43	24	19	19	23	52	35	27	5	1	1

Engineer	Date	Building	Room	Sensitive Instrument	Y Direction - Vibration Velocity Lfeq Levels, micro-inches/second																				
					Third-Octave Frequency Band (Hz)																				
					1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100
SBH	4/28/2009	Engineering - 089	122	EGL - Rm 122 - Dynamic Material Analyzer/MTS Tytron 250	108	79	53	44	42	32	23	18	13	15	17	12	11	19	18	14	8	7	6	4	9
SBH	4/28/2009	Physics Bldg - 082	1357	PHY - Rm 1357 - SQUID 1/SQUID 2	89	56	33	25	29	31	26	20	24	21	26	55	220	153	177	402	44	48	44	23	26
SBH	4/28/2009	Physics Bldg - 082	2317	PHY - Rm 2317	44	26	21	15	18	24	19	17	29	23	20	20	22	11	7	13	4	3	3	3	3
SBH	4/28/2009	Kim Engineering - 225	Clean Room 2nd Floor	KEB - Clean Room - Direct Writing E Beam System	43	29	19	20	50	67	90	49	68	62	78	68	47	31	21	27	17	15	26	13	12
SBH	4/28/2009	AV Williams - 115	1324	AVW - Rm 1324 - Cryogenic System, pneumatic system	64	55	34	24	25	68	32	25	22	25	24	23	15	9	6	4	4	3	5	2	2
SBH	4/28/2009	Kim Engineering - 225	1237C	KEB - Rm 1237C - X-ray, Field Emission Electron Microscop	16	12	8	7	16	26	23	17	13	17	18	36	13	16	29	16	5	3	6	2	1
SBH	4/28/2009	Kim Engineering - 225	1237B	KEB - Rm 1237B - Hitachi SU-70 SEM	32	21	15	12	18	26	27	19	13	18	17	31	12	21	17	14	4	3	5	2	2
SBH	4/28/2009	Chemistry - 091	B0128	CHM - Rm B0128 - 2 Nuclear Magnetic Resonance	26	19	13	11	18	22	19	19	16	18	16	19	9	22	19	8	4	7	10	2	2
SBH	4/28/2009	Chemistry - 091	B0117	CHM - Rm B0117	25	21	18	17	22	25	25	22	20	23	21	21	13	41	33	12	7	5	4	3	4
SBH	4/29/2009	Computer Space Sciences - 224	B0223	CCS - Rm B0223 - Laser on table, pneumatic isolation	42	31	21	16	17	26	25	21	15	37	31	17	27	30	12	20	15	6	4	4	3
SBH	4/29/2009	Computer Space Sciences - 224	B0213	CCS - Rm B0213 - Laser on table, pneumatic isolation	46	33	21	13	18	31	30	30	20	29	34	20	23	16	10	17	6	4	7	2	1
SBH	4/29/2009	Marie Mount Hall - 046	3416K	MMH - Rm 3416K - Brain Wave Research	55	41	29	25	27	32	72	25	10	20	27	52	88	81	46	108	76	64	161	141	24
SBH	4/29/2009	Energy Research Facility - 223	202	ERF - Rm 202 - No Sensitive Equipment	12	9	7	6	14	48	29	14	14	20	18	13	11	6	7	11	7	3	4	3	5
SBH	4/29/2009	Microbiology - 231	0207E	MCB - Rm 0207E - SEM Room	17	12	9	11	27	30	29	46	31	33	40	25	21	27	22	48	11	12	11	8	4
JVC	4/28/2009	Engineering - 089	0128 CALCE Lab	EGL - Rm 0128 CALCE Lab	59	44	33	25	29	24	20	17	13	20	40	12	10	19	12	10	6	6	7	3	6
JVC	4/28/2009	Engineering - 089	1177	EGL - Rm 1177	70	54	37	32	29	39	37	78	84	37	55	59	62	137	112	64	85	57	74	120	24
JVC	4/28/2009	Physics - 082	2219	PHY - Rm 2219	32	24	19	14	23	32	36	35	19	16	59	162	154	92	66	55	32	25	33	17	20
JVC	4/28/2009	Physics - 082	2321	PHY - Rm 2321 - JEOL JSPM-4500A	24	15	10	8	14	21	17	15	26	21	18	19	22	11	8	11	4	4	3	3	4
JVC	4/28/2009	Kim Engineering - 225	SubFab Mech. Rm	KEB - Rm Subfab Mech - No Sensitive Equipment	382	263	181	129	101	74	53	41	29	25	22	16	13	14	10	18	7	16	34	8	22
JVC	4/28/2009	AV Williams - 115	1322	AVW - Rm 1322 - Electron Beam	51	37	27	25	62	216	99	77	66	77	77	73	41	30	15	11	7	5	7	4	1
JVC	4/28/2009	Kim Engineering - 225	1237D	KEB - Rm 1237D - JEOL JXA-8900R WD/ED, Micro Analyz	32	23	14	10	17	27	22	17	13	18	18	34	13	17	27	19	4	4	7	1	1
JVC	4/28/2009	Kim Engineering - 225	Rm Adjacent to 1237B	KEB - Rm 1237B - Transmission Electron Microscope	19	14	10	9	20	18	24	20	12	15	16	15	10	16	17	13	3	3	6	1	2
JVC	4/28/2009	Chemistry - 091	B0127	CHM - Rm B0127 - X-ray Photoelectron Spectroscopy Cent	45	25	14	10	18	20	18	18	14	18	16	14	8	26	30	11	5	16	46	3	2
JVC	4/28/2009	Chemistry - 091	B0112	CHM - Rm B0112 - X-ray Crystallography	49	30	17	11	19	22	21	18	15	19	17	15	18	49	24	10	6	7	7	2	4
JVC	4/29/2009	Biosciences Research - 144	1205&1203	BPS - Rm 1205/1203 - Compound and Laser Scanning Mic	39	28	22	34	85	47	36	54	78	101	58	42	38	25	41	40	26	33	52	13	31
JVC	4/29/2009	Computer Space Sciences - 224	B0202	CSS - Rm B0202 - Quantum Information ion trap	236	178	131	103	75	58	49	37	30	59	134	24	42	65	28	27	22	13	9	8	7
JVC	4/29/2009	Marie Mount Hall - 046	Ground Floor by Rm 400	MMH - Rm 400	200	151	112	85	65	51	43	31	26	49	129	25	107	119	162	48	45	34	35	20	29
JVC	4/29/2009	Energy Research Facility - 223	202B	ERF - Rm 202B - Scanning Electron Microscope	15	11	9	7	14	47	26	13	11	17	17	9	13	6	5	7	7	15	32	6	45
JVC	4/29/2009	Biomolecular Sciences - 413	1116	BMS - Rm 1116 - X-ray (produces vibration)	42	25	16	11	18	32	29	15	15	14	15	13	8	8	12	15	5	15	36	13	12
JVC	4/29/2009	Microbiology - 231	0107F TEM Room	MCB - Rm 0107F TEM - Convolution Microscope	42	28	19	16	27	30	29	47	31	30	36	20	15	19	17	30	19	14	6	2	3

Engineer	Date	Building	Room	Sensitive Instrument	Z Direction - Vibration Velocity Lfeq Levels, micro-inches/second																				
					Third-Octave Frequency Band (Hz)																				
					1	1.25	1.6	2	2.5	3.15	4	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80	100
SBH	4/28/2009	Engineering - 089	122	EGL - Rm 122 - Dynamic Material Analyzer/MTS Tytron 250	97	74	56	46	36	27	24	41	47	54	69	51	36	50	52	45	15	34	47	14	48
SBH	4/28/2009	Physics Bldg - 082	1357	PHY - Rm 1357 - SQUID 1/SQUID 2	106	82	101	70	87	114	130	163	198	253	356	1289	1541	404	379	941	151	139	149	76	76
SBH	4/28/2009	Physics Bldg - 082	2317	PHY - Rm 2317	41	21	16	13	10	7	8	18	24	23	18	20	37	13	15	16	6	6	4	4	3
SBH	4/28/2009	Kim Engineering - 225	Clean Room 2nd Floor	KEB - Clean Room - Direct Writing E Beam System	65	48	30	21	15	14	17	29	47	63	80	155	253	142	115	162	65	54	96	38	49
SBH	4/28/2009	AV Williams - 115	1324	AVW - Rm 1324 - Cryogenic System, pneumatic system	80	73	47	29	19	15	15	21	48	75	76	71	57	36	34	19	9	6	7	5	3
SBH	4/28/2009	Kim Engineering - 225	1237C	KEB - Rm 1237C - X-ray, Field Emission Electron Microscop	17	13	8	6	5	5	7	12	26	35	44	43	29	32	50	14	5	5	8	3	2
SBH	4/28/2009	Kim Engineering - 225	1237B	KEB - Rm 1237B - Hitachi SU-70 SEM	56	40	28	19	16	11	10	15	28	36	46	43	26	36	51	20	5	4	8	3	3
SBH	4/28/2009	Chemistry - 091	B0128	CHM - Rm B0128 - 2 Nuclear Magnetic Resonance	38	27	18	13	11	11	13	27	42	64	84	89	80	264	362	47	47	29	30	13	12
SBH	4/28/2009	Chemistry - 091	B0117	CHM - Rm B0117	33	32	33	32	21	24	23	34	41	65	117	115	97	276	135	35	28	23	20	10	7
SBH	4/29/2009	Computer Space Sciences - 224	B0223	CCS - Rm B0223 - Laser on table, pneumatic isolation	15	11	9	7	5	6	8	12	23	41	52	141	87	78	52	86	38	24	16	10	6
SBH	4/29/2009	Computer Space Sciences - 224	B0213	CCS - Rm B0213 - Laser on table, pneumatic isolation	39	26	15	13	11	9	11	18	29	48	72	157	167	163	52	68	33	18	15	5	5
SBH	4/29/2009	Marie Mount Hall - 046	3416K	MMH - Rm 3416K - Brain Wave Research	18	16	20	20	19	24	35	40	53	87	132	343	593	249	199	223	140	128	210	73	60
SBH	4/29/2009	Energy Research Facility - 223	202	ERF - Rm 202 - No Sensitive Equipment	11	9	7	6	6	7	13	20	59	92	99	54	44	29	19	15	14	12	18	20	13
SBH	4/29/2009	Microbiology - 231	0207E	MCB - Rm 0207E - SEM Room	18	11	9	7	7	11	20	50	68	141	228	119	89	88	82	120	33	36	26	7	5
JVC	4/28/2009	Engineering - 089	0128 CALCE Lab	EGL - Rm 0128 CALCE Lab	67	49	37	31	23	20	23	39	50	62	75	34	35	54	51	50	24	29	54	11	17
JVC	4/28/2009	Engineering - 089	1177	EGL - Rm 1177	83	60	41	37	27	27	36	63	99	131	171	204	225	385	175	147	100	131	175	192	83
JVC	4/28/2009	Physics - 082	2219	PHY - Rm 2219	109	84	57	46	35	30	36	50	52	65	92	182	420	332	173	151	157	163	102	67	39
JVC	4/28/2009	Physics - 082	2321	PHY - Rm 2321 - JEOL JSPM-4500A	17	13	10	7	6	6	8	19	23	23	19	20	35	15	18	21	7	8	8	5	5
JVC	4/28/2009	Kim Engineering - 225	SubFab Mech. Rm	KEB - Rm Subfab Mech - No Sensitive Equipment	137	87	59	45	33	27	23	28	42	60	76	82	55	53	52	95	36	47	44	17	15
JVC	4/28/2009	AV Williams - 115	1322	AVW - Rm 1322 - Electron Beam	71	45	31	23	19	21	36	65	177	284	307	279	241	152	79	39	17	11	13	4	4
JVC	4/28/2009	Kim Engineering - 225	1237D	KEB - Rm 1237D - JEOL JXA-8900R WD/ED, Micro Analyz	27	16	10	7	5	5	7	11	25	36	44	39	29	30	28	20	4	5	6	2	2
JVC	4/28/2009	Kim Engineering - 225	Rm Adjacent to 1237B	KEB - Rm 1237B - Transmission Electron Microscope	26	18	13	10	7	7	9	16	29	39	48	46	31	56	37	17	5	7	17	3	6
JVC	4/28/2009	Chemistry - 091	B0127	CHM - Rm B0127 - X-ray Photoelectron Spectroscopy Cent	56	32	19	13	9	9	13	29	36	51	58	94	59	193	330	64	35	47	122	9	6
JVC	4/28/2009	Chemistry - 091	B0112	CHM - Rm B0112 - X-ray Crystallography	53	32	19	12	9	9	13	30	42	60	94	86	102	448	206	49	41	49	27	18	19
JVC	4/29/2009	Biosciences Research - 144	1205&1203	BPS - Rm 1205/1203 - Compound and Laser Scanning Mic	76	57	53	41	46	48	56	76	118	259	286	174	271	286	388	169	146	114	156	64	106
JVC	4/29/2009	Computer Space Sciences - 224	B0202	CSS - Rm B0202 - Quantum Information ion trap	171	135	101	86	64	53	44	37	37	71	150	207	206	258	72	109	61	31	24	9	9
JVC	4/29/2009	Marie Mount Hall - 046	Ground Floor by Rm 400	MMH - Rm 400	225	155	108	91	65	52	44	38	37	63	144	76	220	195	242	133	113	78	87	48	63
JVC	4/29/2009	Energy Research Facility - 223	202B	ERF - Rm 202B - Scanning Electron Microscope	16	11	9	6	5	14	11	19	51	84	86	48	33	18	15	24	8	75	165	16	62
JVC	4/29/2009	Biomolecular Sciences - 413	1116	BMS - Rm 1116 - X-ray (produces vibration)	93	48	24	14	8	7	16	23	48	70	100	110	75	43	37	53	73	96	133	87	72
JVC	4/29/2009	Microbiology - 231	0107F TEM Room	MCB - Rm 0107F TEM - Convolution Microscope	16	11	9	7	6	10	19	47	64	135	215	129	100	96	73	127	19	19	21	6	6